Aalto-yliopisto
Insinööritieteiden korkeakoulu

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Powertrain development scenarios for road transport in Finland, Sweden and Norway

Thesis submitted for approval of the degree of Master of Science in Technology.

Espoo 26.11.2017
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Abstract of master's thesis

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Title of thesis Powertrain development scenarios for road transport in Finland, Sweden and Norway		
Degree programme Master's Programme in Energy Technology		
Major/minor Energy technology		**Code** K3007
Thesis supervisor Professor Martti Larmi		
Thesis advisor(s) Mika Aho		
Date 26.11.2017	**Number of pages** 78	**Language** English

Abstract

A significant share of global GHG emissions arises from the road transport segment. The road transport emissions are still increasing and the segment is heavily dependent on fossil fuels. Vehicle efficiency improvements, a shift to vehicles with more efficient powertrains and the use of biofuels can contribute to GHG emission reductions in the road transport segment. The emission reduction potentials of these factors are examined for the road transport sector in Finland, Sweden and Norway.

The focus of this study is on powertrains for passenger cars and light commercial vehicles. Early adopters have succeeded in demonstrating that battery electric vehicles can provide the necessary features to replace conventional vehicles. When using clean electricity, battery electric vehicles provide significant reduction of emissions due to the high efficiency of the electric powertrain. The high price and low driving range are often considered the most important barriers for electric vehicle adoption. Both of these parameters are related to the battery of the vehicle. Falling battery manufacturing costs and technology advancements allows for lower prices and higher driving ranges of electric vehicles, which supports a scenario with fast adoption of battery electric vehicles in the passenger car segment.

The development of GHG emissions from road transport in Finland, Sweden and Norway is examined using a scenario approach. An electric and a conservative scenario were created for the share of powertrains in the future vehicle sales. Additional scenarios were created for total transport need, vehicle efficiency improvement and fuel consumption. To assess the impact of these development scenarios, a quantitative model was created were results can be obtained regarding GHG emissions, fuel consumption and the vehicle fleet in all three countries for 2017-2050.

Emission reductions in the scenarios are compared to national emission reduction targets in Finland, Sweden and Norway. The results indicate that the targets are ambitious and challenging to achieve. Forecasted growth in transport need and the slow renewal of the vehicle fleets, hinder the reduction of road transport GHG emissions. The slow fleet renewal causes the impact of efficiency improvements and more efficient powertrains to only gradually have an impact on the total emissions. Due to the inferior energy density of batteries compared to liquid fuels, the road transport sector will be dependent on liquid fuels for many years to come, even in a scenario with rapid electrification. Thus, vehicle efficiency improvements, a shift to vehicles with more efficient powertrains and the use of biofuels are all needed to reduce the emissions from road transport.

Keywords GHG emissions, road transport, electric vehicle, vehicle fleet, model, scenario, powertrain adoption, biofuel, hybrid vehicles

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Sammandrag av diplomarbetet

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Huvud-/biämne Energiteknik		**Kod** K3007
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Datum 26.11.2017	**Sidantal** 78	**Språk** Engelska

Sammandrag

En betydande del av de globala växthusgasutsläppen härstammar från vägtrafiken. Utsläppen från vägtrafiken växer fortfarande och sektorn är starkt beroende av fossila bränslen. Effektivitetsförbättringar av fordon, nya drivlinor och biobränslen kan bidra till att minska växthusgasutsläppen från vägtrafiken. Potentialen för dessa faktorer granskades för vägtrafiken i Finland, Sverige och Norge.

Denna studie fokuserar på drivlinor för personbilar och lätta lastbilar. Elbilar har visat sig ha de nödvändiga egenskaperna för att kunna ersätta en stor del av traditionella bilar med förbränningsmotorer. Eftersom elbilen har en mycket hög verkningsgrad, är utsläppen betydligt lägre då ren elektricitet används. Priset på elbilar är dock betydligt högre än priset på traditionella bilar. Det höga priset och den korta räckvidden anses ofta vara hinder för en stor utbredning av elbilar i bilparken. Båda dessa parametrar är beroende av elbilens batteri. Fallande produktionskostnader för batterier och tekniska förbättringar har möjliggjort lägre priser och längre räckvidd för elbilar. Denna trend förväntas fortsätta, vilket ger stöd för ett scenario med en snabb utbredning av elbilar i bilparken.

Utvecklingen av växthusgasutsläpp från vägtrafiken i Finland, Sverige och Norge granskas med hjälp av olika scenarier. Två scenarier skapades för andelen av olika drivlinor i bilförsäljningen. Ytterligare scenarier skapades för totalt transportbehov, effektivitetsförbättringar av fordon och bränsleförbrukning. En kvantitativ modell konstruerades för att uppskatta inverkan av dessa scenarier på bilparken, växthusgasutsläpp och bränsleförbrukning i alla tre länder fram till år 2050.

Reduktionen av växthusgasutsläpp i scenarierna jämfördes med nationella mål för reduktion av vägtrafikens växthusgasutsläpp. Resultaten visar att de nationella målen är svåra att nå, då förväntad tillväxt i transportarbete och den långsamma förnyelsen av bilparken hindrar en snabb minskning av växthusgasutsläpp. Fordon stannar många år i bilparken, vilket resulterar i att effektivitetsförbättringar och nya drivlinor endast gradvis har en inverkan den totala bilparken. På grund av den avsevärt lägre energitätheten för batterier jämfört med flytande bränslen, förväntas vägtrafiken vara beroende av flytande bränslen i många år framöver, även i ett scenario med snabb utbredning av elbilar. Därmed kan ingen teknik uteslutas, utan effektivitetsförbättringar, nya drivlinor och biobränslen är alla nödvändiga för att minska växthusgasutsläppen från vägtrafiken.

Nyckelord Växthusgasutsläpp, vägtrafik, elbil, bilparken, modell, scenarier, drivlinor, biobränsle, hybridbilar

Preface

This master's thesis was written for St1 Nordic Oy. The road transport model used and described in this thesis was created together with Eero Kilpeläinen and Matteo Giacosa. First and foremost, I wish to thank Eero and Matteo for the time we worked together, their knowledge and encouragement.

I wish to thank my advisor Mika Aho, for providing the opportunity to write my thesis for St1. I am grateful for all the expertise and interesting insights that he was able to provide. I would also like to thank Irina Karamushko for taking ownership of the model after the project and all my other colleagues at St1, who helped me during the project.

My special thanks to my supervisor Martti Larmi for his guidance and support. I would also like to express my appreciation to the statistics agencies in Finland, Sweden and Norway, for providing data to the model and for helping me understand the statistics.

Finally, I would like to thank my family, girlfriend and friends for their support and encouragement.

Mathias Westerholm

Espoo 26.11.2017

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Abbreviations

BEV	Battery electric vehicle
BMS	Battery management system
CNG	Compressed natural gas, also referring to the powertrain
CO_2eq.	Carbon dioxide equivalent
ETBE	Ethyl tert-butyl ether
EV	Electric vehicle, a vehicle with an electric drivetrain
FAME	Fatty-acid methyl esters
FCV	Fuel cell vehicle
FFV	Flexi-fuel vehicle
GHG	Greenhouse gases
HBEFA	Handbook Emission Factors for road transport
HEV	Hybrid electric vehicle
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
LCO	Lithium Cobalt Oxide
$LiPF_6$	Lithium hexafluorophosphate
Li-S	Lithium-sulphur
LMO	Lithium Manganese Oxide
MTBE	Methyl tert-butyl ether
NCA	Lithium Nickel Cobalt Aluminum Oxide
NEDC	New European driving cycle
NMC	Lithium Nickel Manganese Cobalt Oxide
NO_x	Nitrogen oxides, mainly nitric oxide and nitrogen dioxide
OEM	Original equipment manufacturer
OLS	Ordinary least squares
PHEV	Plug-in hybrid electric vehicle
SCR	Selective catalytic reduction
SEI	Selective electrolyte interface
SOC	State of charge
TTW	Tank-to-wheel
vol%	volumetric share
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
WTW	Well-to-wheel

1 Introduction

In 2015, the growth in global CO_2 emissions was stalled, as the total CO_2 emissions reached a level of 32,3 $GtCO_2$, representing a 0,1 % decrease from the level in 2014. The transport segment was responsible for 24 % of the global CO_2 emissions from fuel combustion, compared to a share of 23 % in 2014. Thus, the emissions from transport continued to grow and showed no signs of a decrease. Of the transport segment emissions, around three quarters were related to road transport, and therefore road transport plays a large role in achieving global GHG emission reductions. [1], [2].

Finland, Sweden and Norway have set ambitious national targets for GHG reduction in road transport as shown in Figure 1. The Finnish target is set to 50 % GHG emission reduction by 2030, compared to the level of 2005, as defined in the national climate and energy strategy for 2030 [3]. Sweden has set a target on 70% reduction in road transport GHG emissions between 2010 and 2030, as a step towards a completely fossil free road transport sector [4]. Norway has set a target on 40 % GHG emission reduction by 2030 compared to the level of 1990 [5]. Applying the reduction directly to road transport, the GHG emissions should be reduced by 55% compared to the level of 2015. Comparing the target levels to the emissions in 2016, the annual reduction until 2030 should be 5,2 % in Finland, 7,9 % in Sweden and 5,5 % in Norway. Relating this to the achieved average annual reductions of 1,9 % in Finland, 2,2 % in Sweden and 0,8 % in Norway between 2010 and 2016, the reduction targets are definitely ambitious.

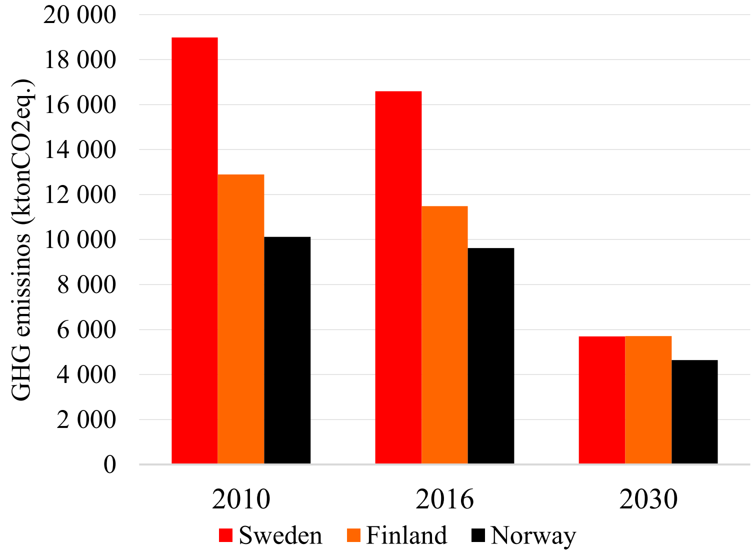

Figure 1 National road transport GHG emissions in 2010 and 2016 as well as national targets for 2030 [3]–[5].

The aim of this study was to create scenarios for the development of road transport GHG emissions in Finland, Sweden and Norway, and compare the development with the national reduction targets. To do this, a quantitative bottom-up road transport model was constructed, to assess the impact on GHG emissions and energy demand from different development scenarios. In this study, the model is referred to as the Matero model, or simply the model. When referring specifically to the model and information used for one of the three countries, the terms the Finnish, the Swedish and the Norwegian model are used.

For modelling the future vehicle fleet development, the model relies on constructed powertrain split scenarios and a stock-flow-cohort methodology. A powertrain split is the share of powertrains for new vehicle registrations, where powertrain refers to a vehicle's drivetrain, or the components driving the vehicle forward. Additional assumptions, such as for annual efficiency improvements, energy carrier compositions and transport need forecasts, are incorporated to deliver scenario results related to vehicle fleet development, energy consumption and GHG emissions. A scenario approach is necessary, due to the great amount of uncertainty related to many factors in road transport, such as technology and cost development of powertrains and biofuels, future total transport need and different policies and subsidies.

The model was created as a part of a research project. The focus of this study is on development scenarios for light-duty vehicles, as well as on calculation of fuel and energy consumption, quantification of national road transport fuel consumption and national forecasted transport need. Further elaborations related to the Matero model methodology can be found in Kilpeläinen [6]. Insights related to the heavy-duty segment and annual efficiency improvements can be found in Giacosa [7].

Light-duty vehicles are passenger cars and light commercial vehicles, and these vehicle segments can be considered to be relatively similar when constructing development scenarios. As passenger cars make up over 80% of the total vehicle fleet in all three countries, they are put in the center of the analysis. In order to construct reasonable powertrain development scenarios, the emission reduction potential for various powertrains is assessed in chapter 2. Electric vehicles provide significant emission reductions, due to the higher efficiency of the electric powertrain compared to conventional internal-combustion engines and the low emission factor of electricity in Finland, Sweden and Norway. However, the higher cost of electric vehicles is often considered a barrier to a large and rapid adoption. Therefore, the price of electric vehicles is analyzed, both related to manufacturing costs and total cost of ownership. Other barriers for electric vehicle adoption, such as range, cold weather performance and charging time are also having a significant impact on electric vehicle adoption. These factors are directly related to the electric vehicle battery, which is why fundamentals and developments of battery technology are presented in chapter 3.

Batteries are a large cost component of electric vehicles, but improved technology and manufacturing methods have enabled cost-reductions in the recent years, a trend that is expected to continue [8]. Prospects for falling battery prices as a result of technological advancements, industrial learning and economies of scale are presented in chapter 4. In spite of the extensive analysis, it is hard to find sufficient correlation between any characteristics of electric vehicles and adoption of electric vehicles. For this reason, a method relying on Bass diffusion of technology [9] is used when constructing powertrain development scenarios. This method as well as an electric and a conservative powertrain scenario are described in chapter 5. The scenarios are used in the model, and results are obtained related to road transport energy consumption and GHG emissions for 2017 to 2050.

1.1 Scope and model boundaries

In this study, road transport refers transport activities performed by passenger cars, light commercial vehicles, heavy-duty vehicles and buses. Left out of the scope are motorcycles, mopeds, snowmobiles, agricultural machines, stationary combustion and all other off-road combustion of fuel. Fuel consumption by the military is also excluded, in accordance with IPCC Guidelines [10]. The allocation of fuels to these different activities is described in chapter 6. Estimation of GHG emissions and energy consumption is based on the combustion of all fuel used in road transportation, including propulsion and ancillary services. The ancillary services are generally used to maintain cabin and cargo space temperature, and in HDV vehicles for the handling of cargo. Both well-to-wheel (WTW) and tank-to-wheel (TTW) GHG emissions are considered.

The methodology for estimating energy consumption and GHG emissions from the road transport sector is consistent with the European standard EN 16258 [11] as well as the IPCC Guidelines for National Greenhouse Gas Inventories [10]. The greenhouse gases considered are limited to carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF6). These are the greenhouse gases listed in Annex A of the Kyoto Protocol [12]. The greenhouse gases are not treated separately but always as a group of emissions. No other emissions are accounted for in this study, even though it is noted that reduction of air pollutants is a main driver for development in road transport, as the pollutants cause respiratory and cardiovascular diseases as well as affect the health in general. The most relevant air pollution substances are nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO) and non-methane volatile organic compounds (NMVOC). [13]. Other negative externalities of road transport, such as accidents, noise, congestion and emissions related to vehicle and tire production as well as all road transport emissions not related to the energy carriers, are also left out of the scope.

The Matero model is created for road transport in Finland, Sweden and Norway. Energy demand and GHG emissions in each country are modelled through the vehicles registered in the national vehicle fleets and their odometer mileages. Parameters in the model are adjusted, so that the energy consumption for all energy carriers is on the same level as the energy consumption derived from the fuel sales in the respective countries. Thus, the model cannot account for cross-border fuel consumption, that is, vehicles in the national vehicle fleet fueling in other countries or vehicles from other countries fueling in the country in question. The general assumption is that fuel consumption from foreign vehicles inside e.g. Finland, is compensated for by Finnish vehicles fueling in other countries. The time horizon considered for the development scenarios is 2017 to 2050, even though the model is constructed to enable an extended time horizon. Data related to vehicle fleet, new vehicle registration and fuel consumption from 2012 to 2016 is used as a starting point for each of the development scenarios.

2 Options for GHG emission reduction in the light-duty vehicle segment

Four dimensions are often considered when assessing the options for GHG emission reduction. Two of these are considered in this study. These are powertrain efficiency improvements and more efficient powertrains as well as the use of more sustainable energy carriers with lower GHG intensities. The two other dimensions are reduction in transport activity by e.g. better urban planning and improved logistics and shifting to more energy efficient modes of transport, e.g. a modal shift from passenger cars to public transportation or a modal shift from trucks to railway or marine transport [14]. The focus in this study is on more efficient powertrains and more sustainable energy carriers, mainly related to the passenger car segment. The considered road transport energy carriers are gasoline, diesel, E85, compressed natural gas (CNG), liquefied natural gas (LNG), hydrogen (H_2) and ED95. Among the energy carriers, liquid fuels are the most versatile and have the potential of serving all types of transport. This is mainly due to their high energy density and the fact that they are easy to store and distribute.

Liquid fuels are gasoline, diesel, E85, ED95 and LNG. E85 is a high-blend gasoline fuel with a 85 % maximum volumetric share of ethanol, however during winter the share is closer to 75 % to improve operation in cold conditions. The non-ethanol share is gasoline and denaturants, such as methyl tert-butyl ether (MTBE), ethyl tert-butyl ether ETBE and isobutanol. [15]. ED95 consists of roughly 95 vol% ethanol, ignition improver, MTBE and isobutanol and is mainly used in Sweden [16]. Second in line regarding energy density comes the gaseous fuels CNG and hydrogen, and last electricity stored in batteries. The energy density is largely determining the applicability of certain energy carriers and powertrains, so that vehicles with high energy demand are directed towards liquid fuels.

The powertrains that are considered are based on internal combustion engines (ICE), electric motors and fuel cells. Combinations of ICE and electric motors are also considered, that is, hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs). Powertrains using an internal-combustion engine are gasoline and diesel, including HEV and PHEV variants, compressed natural gas (CNG), liquefied natural gas (LNG), ED95 and flexi-fuel vehicles (FFV). The electric powertrains are battery electric vehicles (BEV) and fuel cell vehicles (FCV). All vehicles, that do not match any of the previous powertrain segments, or vehicles that lack information about powertrain in the vehicle registers, are classified as other. The shares of different powertrains in the vehicle fleet and new registrations for year 2016 are presented in Table 5. A HEV is defined as a vehicle that has an electric powertrain as well as an ICE powertrain, independent on the size of the electric powertrain. A HEV cannot be plugged into the electric grid for charging, which distinguishes it from a PHEV.

Reductions in GHG emissions can be achieved through energy efficiency improvements of existing conventional powertrain technologies, or by introducing new and more efficient technologies. The efficiency improvement of conventional powertrains is studied more in detail in Giacosa [7], while the focus of this study is on powertrain electrification, particularly electric vehicles using a battery for energy storage. Electrification of vehicles comes in many forms, ranging from simple start-stop technologies to pure battery electric vehicles (BEV), thus providing varying levels of efficiency improvements.

Emission reductions can also be a result of energy carriers with lower emission intensities, providing more energy with lower emissions. Emission intensities are defined through emission factors, quantifying the amount of GHG emissions per amount of energy. The various GHG emission factors of energy carriers are accounted for using a well-to-wheel (WTW) and a tank-to-wheel (TTW) approach. WTW emissions account for emission related to the use and the production of the energy carrier, whereas TTW emissions only account for the emissions related to direct use of the energy carrier [17]. An energy carrier can have different WTW GHG intensities depending on the feedstock and production method, whereas the TTW intensity always is the same for a certain energy carrier. As long as a similar combustion is assumed, the TTW emission factor will be the same, as the TTW emissions are related to the combustion or use of the energy carrier [18]. WTW and TTW emission factors for all energy carriers used in the model are presented in Appendix 1. Biofuels can be produced from a large amount of different raw material, and through various processes, resulting in large variation in WTW emission factors. Due to the large variation and uncertainty, it is assumed that biofuels offer 70 % reduction in GHG emissions compared to the corresponding fossil energy carrier. This is elaborated in chapter 6.4.

Over the last years, the efficiency of passenger cars in Finland, Sweden and Norway has slowly been improving, mainly due to efficiency improvements and a shift to diesel vehicles. The diesel powertrain is around 20 % more efficient than the gasoline powertrain, and the increasing share of diesel vehicles have contributed to a higher efficiency [19]. However, the improvement is still marginal, and in order to achieve a significantly more efficient light-duty vehicle fleet, a shift away from the internal combustion engine is needed. The efficiency of the ICE is still increasing, but efficiency improvements are limited due to thermodynamical limits of the combustion process [14]. Figure 2 presents the WTW GHG emissions assumed in the Finnish model for passenger cars registered in Finland in 2016, with a mass in running order between 1400 and 1800 kg. The method for obtaining the efficiency of vehicles is described in chapter 3.

Of the powertrains considered, BEV and FCV using hydrogen produced from renewable sources, have by far the lowest emissions. The low emissions of electric vehicles are largely an effect of the high efficiency of the electric motor and low emission in electricity production. The emission intensity of electricity produced in Sweden is even lower than the electricity produced in Finland, resulting in lower emissions for the battery electric vehicle in Sweden (BEV SWE) than the battery electric vehicle in Finland (BEV FIN). Currently, most of the hydrogen is produced from fossil sources, and the cost of renewable would be high. [20], [21]. For these reasons, the electric powertrain is examined more in detail in the following chapters.

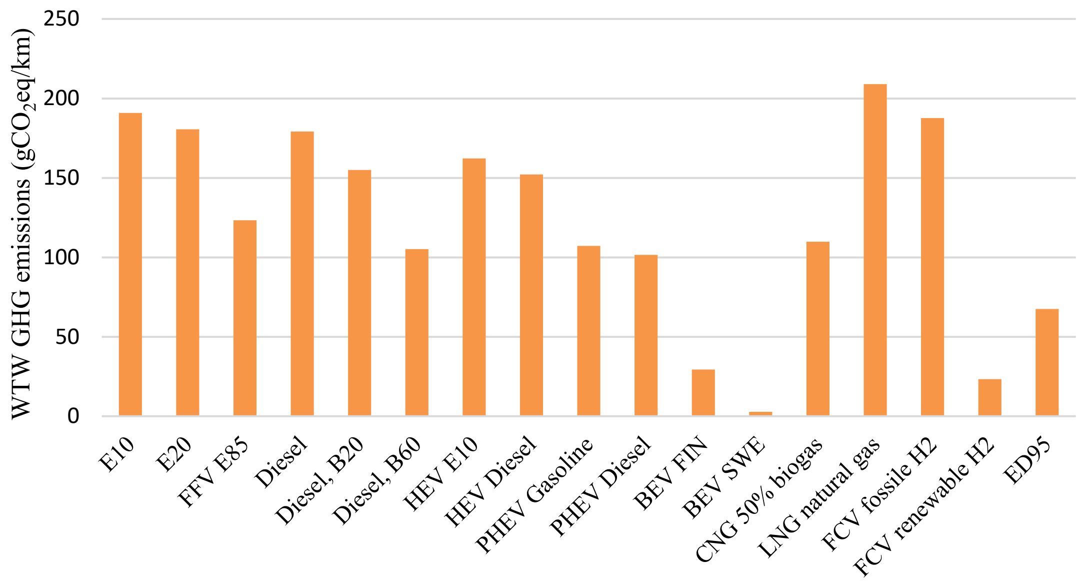

Figure 2 WTW GHG emissions in gCO_2eq/km for different powertrains and energy carriers in the sub-segment PC 1400-1800kg based on vehicles registered in Finland 2016. E10 refers to gasoline with 10 vol% ethanol, E20 to gasoline with 20 vol% ethanol, B20 to diesel with 20 vol% biodiesel and B60 to diesel with 60 vol% biodiesel. Biofuels are considered to provide 70 % reduction of WTW GHG emissions.

2.1 Recent trends in adoption of electric vehicles and customers' perceptions

The global electric vehicle sales have steadily been increasing over the last years and in 2016 there were roughly 750 thousand electric vehicles sold (BEV + PHEV). In the same year, the global electric vehicle fleet grew with 60 %. Lower vehicle costs, extended ranges and generous subsidy schemes have reduced electric vehicle adoption barriers for consumers' in many countries. Six countries had a market share of electric vehicles exceeding 1 % in the light-duty vehicle segment in 2016. Globally, the market share in Norway was by far the highest, with 29 % of new registered vehicles in the light-duty vehicle segment being BEVs or PHEVs. Even so, the electric vehicle fleet still only makes up just 0.2 % of the global passenger car and light commercial vehicle fleet. Some countries having a significantly higher share of electric vehicles, is a result of country-specific subsidies, purchase power and customer preferences. [8].

A Norwegian study examined vehicle owners' perceptions and preferences related to electric vehicles. The study included a survey with 3111 BEV owners, 2065 PHEV owners and 3 080 ICE vehicle owners. Environmental friendliness was seen as the most advantageous characteristics of electric vehicles. Comfort and acceleration were also considered important advantages. Concerning EV parameters, the limited range and charging time was perceived as the biggest disadvantages. Even though the charging time was considered problematic, the perception of home charging was very positive. When respondents were asked about important factors for an increasing BEV market, a longer range and improved availability of fast chargers were considered the most important parameters, followed by keeping the exemption from purchase taxes and toll road charges. From the responses, it is also evident that BEV owners have the most positive conception about BEVs, followed by PHEV owners and ICE vehicle owners.

The high purchase cost is generally considered the most important barrier to a large EV adoption. Even so, among the vehicle owners in the survey, the purchase price was not in general considered as a disadvantage. However, Norwegian customers benefit from major purchase incentives, which make the price of electrical vehicles more competitive. Without the incentives, the high price would likely be considered a disadvantage. [22]. Other studies report the same factors as well as perceived safety, as major barriers to electric vehicle adoption [14], [23], [24]. Introductory cost of new equipment, lock-in effects of existing technology and existing driving practices do also act as barriers, but are not generally perceived by customers [25]. The parameters range, charging time and price are studied in detail in the following chapters.

To compensate for the described disadvantages, major drivers for EV adoption are low GHG emissions, no local air pollutant emissions and low operational costs. Additionally, the image from driving an EV, fast acceleration and high comfort from the silent electric powertrain are also factors influencing the EV adoption. [22]. The negative externalities from road transportation are generally considered as air pollution, environmental damage, noise, accidents and congestion. Electrification of the vehicle fleet can certainly cut air pollution, alleviate environmental damage and reduce noise. [26], [27]. Especially, in bigger cities, the air quality is becoming a problem and might drive the transition to vehicles with zero or low local emissions. This trend can also be seen as cities are creating zones for the use of vehicles with low local air pollutant emissions.

Electric vehicles enable the use of electricity as energy carrier, and when using electricity produced from sources with low GHG emissions, the GHG emissions that can be related to road transport is also reduced. As a result, BEVs and PHEVs are expected to be a major contributor to the reductions of GHG emissions. As long as the carbon intensity of the electricity is low, electric vehicles can offer significant GHG emissions reductions compared to ICE vehicles [28]. This is a challenge for countries that are dependent on coal power generation, but the carbon intensity of the Norwegian, Swedish and Finnish electricity is very low, offering great opportunities for emission reductions. Related to this, EVs connected to the grid can also provide a balancing load, which in turn can support an increased share of variable renewable electricity production. [18].

2.2 Price as a major barrier to EV adoption

Early adopters have succeeded in demonstrating that electric vehicles can provide the necessary features to replace conventional ICE vehicles. Still, major barriers to a widespread EV adaption are considered to be a higher price and an insufficient driving range as described in the previous chapter. Both of these factors are linked to the cost of batteries with high energy density, as cheaper batteries could lower the price and enable larger batteries providing longer ranges. The range anxiety could also be alleviated by improving the charging infrastructure, however, the focus of this study is on improved range and not on the electric vehicle charging infrastructure.

Comparing the purchase price of a BEV, PHEV and gasoline model of the VW Golf in Finland, the price excluding vehicle tax of both the BEV and PHEV is more than double that of the gasoline vehicle. The specifications for the compared vehicles can be seen in Table 1. Performing a simple calculation to calculate the hypothetical cost of the BEV excluding the battery, the battery price is assumed to be 200 €/kWh. The battery is 35.8 kWh, and thus the total battery price is approximately 7200 €. The price of the BEV excluding battery is then 33 600 €, which still is 16 320 € more than the price of the gasoline vehicle. [29]. This gap in cost is surprisingly large, and the cost structure of electric vehicles and batteries in the automotive industry is to a great extent uncertain, due to a lack of information from the vehicle manufacturers. Based on the previous analysis, it is however evident that the higher price of a BEV is not only attributed to the battery price, but also a higher price on other components or differences in the obtained margin.

The high cost of electric vehicles excluding the battery is explained by the automotive industry as a result of low volumes both at the component as the vehicle level. The current vehicle manufacturing process is also a result of extensive industrial learning, where costs have been reduced over many years. With higher volumes, the industry would achieve economies of scale for manufacturing, development, design, integration and marketing costs. The current automotive industry relies on an extensive integrated manufacturing model, where vehicle components are interchangeable among many models and brands, which brings significant cost synergies in the manufacturing process. Components in an electric vehicle, such as electric motors and power electronics, are typically technically mature, but irrespective of this produced in low volumes compared to the automotive industry. [30]. The difference in manufacturing volumes can be described by the fact that in 2016 the total electric vehicle registrations (BEV and PHEV) were around 750 thousand, whereas the total light-duty vehicle registrations were over 80 million [8]. This makes the electric vehicle market share lower than 1 % of the total light-duty vehicle registrations. Thus, the cost of electric vehicles could significantly decrease as the vehicle volumes increase and as the battery prices decrease. Insights into battery technology development are presented in the next chapter.

Table 1 Comparison of a BEV, PHEV and gasoline version of VW Golf [29].

Vehicle	Price excl. vehicle tax	Estimated vehicle tax	Total price	e-range (km)	Battery size (kWh)
Trendline 1,0 TSI 63 kW	17 280 €	3 017 €	20 297 €	-	-
GTE Plug-In Hybrid 150 kW	39 440 €	2 321 €	41 761 €	50	8,7
e-Golf 100 kW	40 770 €	1 512 €	42 282 €	280	35,8

The previous calculation method only considers the production cost of the battery, and not costs for development, integration and margins. To account for this, van der Slot [14] et al. use an integration cost factor of 1,8 in their analysis on powertrain costs from profitable production in 2030. Table 2 presents a simplified version of this analysis. The original equipment manufacturer (OEM) surcharge represents an integration cost factor for profitable manufacturing. The factor accounts for vehicle manufacturers' research and development investments, design and integration costs as well as sales costs and margins. [14]. The incremental cost of a BEV is 7 600 € assuming a battery price of 99 €/kWh and 8 751 with a battery price of 109 €/kWh.

To get the full picture of the costs of driving an electric vehicle, a total cost of ownership (TCO) analysis must be performed. This method includes costs for fuel, maintenance, insurance, taxes, subsidies and depreciation from the customers' perspective. Even though the results of a TCO gives the most realistic view of the vehicle costs, the customers rarely analyze the costs in a similar manner. Previously, it has been shown that the use of TCO results in market prediction is complicated, as the results are not fully reflected in the buying decision. [31]. As the electrification trend in road transportation is quite a new phenomenon, statistically relevant TCO analyses have only recently been published.

Table 2 Cost assumptions for gasoline, BEV and PHEV powertrains in 2030 [14].

Powertrain	Components	2030 cost assumptions	
Gasoline	Total cost	**2 265 €**	**2 265 €**
BEV (range > 400 km)	Battery price (€/kWh)	(99 €/kWh)	(109 €/kWh)
	Batteries (65 kWh)	+ 6435 €	+ 7085 €
	Power electronics, e-motor, wiring	+ 1300 €	+ 1300 €
	ICE conventional powertrain	- 2265 €	- 2265 €
	OEM surcharge	x 1,8	x 1,8
	Total cost	**9 846 €**	**11 016 €**
PHEV (e-range 40-80 km)	Battery price (€/kWh)	(130 €/kWh)	(150 €/kWh)
	Batteries (9 kWh)	+ 1170 €	+ 1350 €
	Power electronics, e-motor, wiring	+ 1100 €	+ 1100 €
	Deconteted engine	- 300 €	- 300 €
	OEM surcharge	x 1,8	x 1,8
	Total cost	**3 546 €**	**3 870 €**

Hagman et al. [31] constructed a customer-focused TCO model for four vehicles on the Swedish market. The vehicles were a Volvo V40 D3 diesel, a Volvo V40 V40 T4 gasoline, a Toyota Prius HEV and a BMWi3 BEV. The parameters used in the analysis were depreciation, fuel costs, total mileage, interest, maintenance costs and insurance costs. The analysis was performed for an ownership of three years; thus the vehicles were bought in the beginning of year one, and subsequently sold in the end of year three. The methods and parameter values used in Hagman et al. [31] were used as a base for the TCO in this study, and the results are presented in Table 3. Letting TCO_i denote the total cost of ownership for vehicle $i = 1,2,3,4$, the TCO calculation can be described as

$$\boldsymbol{TCO_i = PP_i - RP_i + FC * D + \left(\frac{rP}{1-(1+r)^{-N}} N - P\right) + IC + M + T} \tag{1}$$

where PP is the purchase price, RP the resell price, FC the fuel cost in liter per kilometer, D the mileage in kilometer, r the monthly effective tax rate, N the number of months of payment, P the borrowed amount, IC the insurance cost, M the maintenance costs and T the taxes and subsidies. The purchase prices, fuel prices and insurance costs were based on actual prices in Sweden. The effective tax rate was considered to be 4.2 % annually and the borrowed amount 80 % of the purchase price. The BEV has less moving parts and requires very little maintenance, which calls for the lower maintenance costs. The warranty was considered to cover all repair costs over the three-year period for the BMWi3, whereas the maintenance and repair costs for the other vehicles were based on the manufacturers' estimates. The largest share of the costs arises from depreciation, the decrease in value over the three-year period. The depreciation rate, the difference between the purchase and the sales price after a certain time period, can vary significantly between cars.

There is still some uncertainty on the lifetime of BEVs, especially related to the lifetime of the battery. One of the few new generation BEVs that have been sold in large volumes over at least a period of three years is the Nissan Leaf SV. An analysis on the depreciation of these vehicles over three years, showed that the depreciation rate was 44 %, meaning that 64 % of the initial value is still left after three-year period. A depreciation rate of 50 % is typically used in leasing and financing models. Therefore, the depreciation rate was considered to be 50 % for all the four vehicles. Hagman et al. [31]. It is worth noticing, that the subsidies on electric vehicles make the depreciation calculation more complicated, and in this analysis the depreciation was considered excluding subsidies.

Table 3 Total cost of ownership (€) for four vehicles over a three-year period with a mileage of 15 000 km annually. In parentheses, the share of total TCO per cost factor.

	Diesel		Gasoline		HEV		BEV	
Purchase price	25 630		25 210		28 824		35 609	
Depreciation	12 815	(64 %)	12 605	(60 %)	14 412	(68 %)	19 906	(105 %)
Fuel costs	4 133	(21 %)	5 814	(27 %)	3 391	(16 %)	632	(3 %)
Insurance cost	908	(5 %)	844	(4 %)	714	(3 %)	926	(5 %)
Maintenance costs	374	(2 %)	374	(2 %)	1 029	(5 %)	0	(0 %)
Taxes and subsidies	343	(2 %)	189	(1 %)	0	(0 %)	-4 202	(-22%)
Interest	1 355	(7 %)	1 333	(6 %)	1 524	(7 %)	1 660	(9 %)
TCO	**19 927**		**21 158**		**21 070**		**18 922**	

In the TCO analysis, the BMWi3 benefits from a lower fuel cost, whereas the other vehicles benefit from lower depreciation, as seen in the results presented in Table 3. For the gasoline vehicle, 60 % of the TCO is related to depreciation and 27 % related to fuel costs. For the BMWi3, depreciation accounts for 105 % of the TCO and fuel costs only for 3 %. The depreciation exceeds 100 %, as the subsidy is not taken into account in the depreciation calculation. This puts light on the significant impact of the subsidy of electric vehicles. Taxes on fuels are included in the fuel costs, which further subsidies the BEV due to lower total taxation, even though this is not seen as a cost in the factor taxes and subsidies. The lower depreciation of the ICE vehicles is directly related to the lower purchase price.

As seen in the results, electric vehicles can be a cost-efficient alternative from a TCO perspective, with an annual mileage of 15 000 km. Electric vehicles benefit from higher mileages, as the fuel costs per kilometre is lower when using electricity compared to gasoline and diesel. The TCO dependency on mileage is illustrated in Figure 3. The diesel vehicle becomes more cost-efficient than the BEV with an annual mileage of 11 000 km. Similarly, the gasoline vehicle is more cost-efficient than the BEV with an annual mileage of 9 500 km. Of the vehicles registered in the Swedish vehicle fleet at any point of the year in 2016, 3 million had a mileage exceeding 11 000 km which represents 55 % of the total vehicle fleet. There were 4 million vehicles driving more than 9 500 km, which represents 74 % of the vehicle fleet. Newer vehicles typically have higher mileages, and 93 % of the vehicles registered in 2013-2015 had higher mileage than 11 000 km. [32]. Thus, it can be concluded that electric vehicles can be cost-efficient from a TCO perspective and that there is a significant discrepancy between electric vehicle total cost of ownership and purchase price.

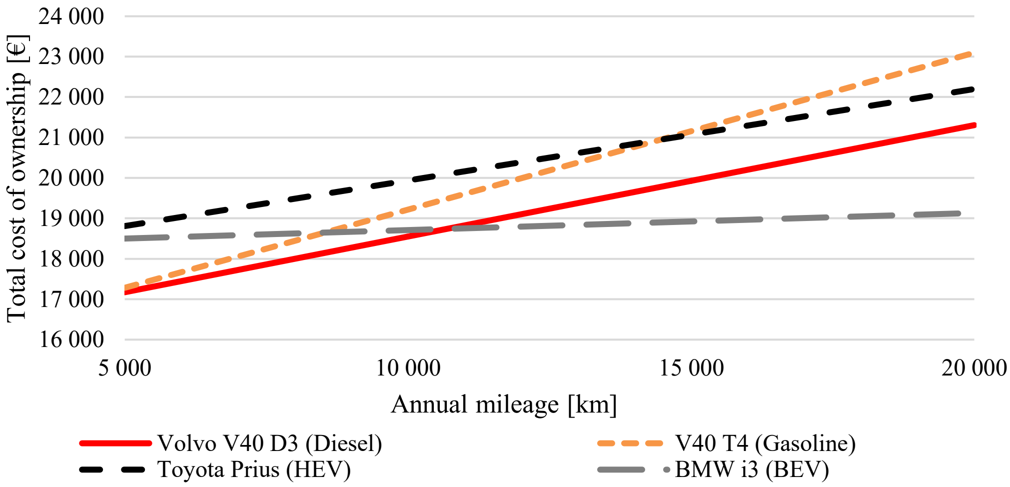

Figure 3 Total cost of ownership as a function of mileage for four vehicles over a period of three years.

2.3 Subsidies and benefits promoting the adoption of electric vehicles

The subsidy included in the total cost of ownership analysis is based on regulation SFS 2016:1360 and entitle vehicles registered in Sweden with lower CO_2 emissions than 50 gCO_2/km to a subsidy. BEVs can receive a maximum of 40 000 SEK in subsidy, and PHEVs can maximally receive 20 000 SEK [33]. This subsidy significantly changes the cost-efficiency of a BEV in the TCO calculation, and demonstrates the importance of including nationally specific taxes in the cost analysis. A similar direct subsidy does not exist in Finland, but a 6 million annual subsidy for 2018-2021 for purchasing BEVs and for conversion of existing gasoline vehicles to FFVs and CNG-vehicles has been proposed [34]. Assuming that the conversion of existing gasoline vehicles would be very minor, most of the subsidy would go to promoting new BEVs. In the electric scenario developed in this study, the registration of BEVs in 2020 is 7 124, which makes the per vehicle subsidy only 842 €. In this scenario, the total registrations of passenger cars in 2020 is 120 834 vehicles, which make the BEV share 5,9 %. Thus, the subsidy could be sufficient as long as the number of BEVs stay very small, but it would not support a larger adoption of BEVs.

Direct subsidies are not the only method used for promoting alternative powertrains. Tax exemptions and other benefits like allowing driving in bus lanes, exemptions from road tolls and parking assigned for alternative powertrains are also used. The Finnish taxation on vehicles provides significant monetary benefits for vehicles with low emissions in the form of lower taxes. The Finnish taxation on vehicles consists of a car tax and a vehicle tax. The car tax is defined in the car tax act (1482/1994) [35], and is paid when the vehicle is included for the first time in the Finnish vehicle register. The tax is based on the vehicles retail price and its CO_2 emissions, and ranges from 5-50 % of the total retail price including taxes. [35]. The vehicle tax, as in Finnish regulation (1281/2003) [36], is collected for each day a vehicle is in the Finnish vehicle registered and allowed to drive. The tax consists of two separate components. The first one is based on CO_2 emissions and ranges from 69.71-617.94 €/year depending on the vehicle specifications. The other one, called powertrain tax, is paid for vehicles that do not use gasoline as fuel and is dependent on powertrain and mass. The powertrain tax is 0.055 €/day/100 kg for a diesel vehicle, 0.015 €/day/100 kg for a BEV and 0.005 €/day/100 kg for a gasoline PHEV. For a vehicle with a mass of 2000 kg, this sums up to 401.5 € annually for a diesel vehicle, 109.5 € for a BEV and 36.5 € for a gasoline PHEV. [36]. In addition to the car tax and vehicle tax, there is an excise tax on fuels. The excise tax on liquid fuels is defined in Finnish regulation (1472/1994) [37] and the excise tax on electricity in Finnish regulation (1260/1996) [38]. The excise tax consists of three components. The first one is based on energy content, the second one on CO_2 emissions and the last one is a fixed contingency fee. In 2017 the total excise tax in eurocent per liter is 53,02 cent/l for diesel and 70,25 cent/l for gasoline. The excise tax on household electricity is 2,253 cent/kWh.

To quantify the vehicle taxation in Finland, five vehicles were compared using the Finnish Transport Safety Agency car comparison tool [39]. Car tax, vehicle tax and excise tax, as described in the previous section, was included in the comparison Powertrains compared were diesel, gasoline, gasoline HEV, gasoline PHEV and BEV. Vehicles with an approximate price of 36 000 € and with a similar equipment level were selected for the comparison. The diesel vehicle was a Ford Mondeo 2,0 TDCi 150hv M6 ST-line Wagon, the gasoline a Volvo S60 T3 Business Classic Summum, the gasoline HEV a Kia Niro 1,6 GDI Hybrid Business Luxury DCT 18, the gasoline PHEV a Hyundai IONIQ plug-in DCT Style and the BEV a Nissan Leaf Visia 30 kWh.

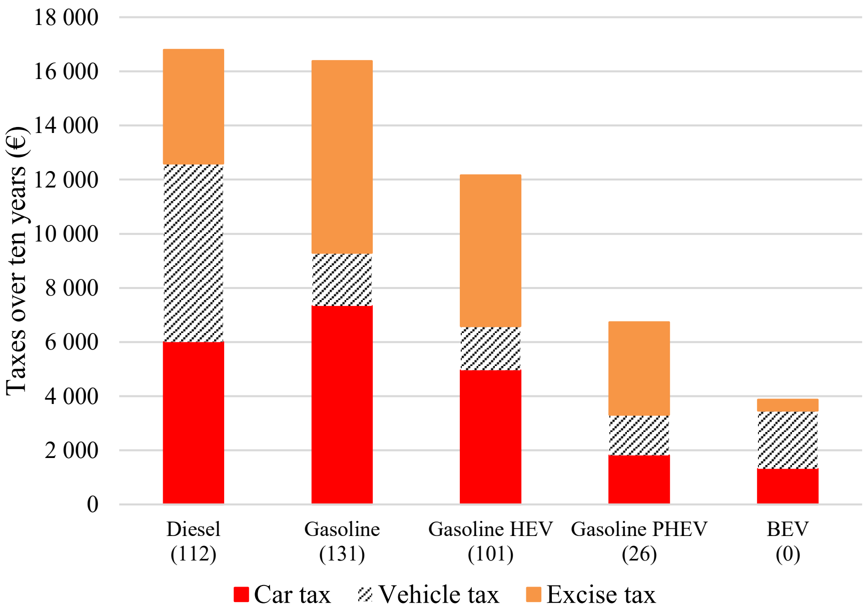

Figure 4 Estimated taxation on vehicles over a period of ten years in Finland. Assumed that vehicles are driven 18 000 km annually and that the PHEV covers 55% of the mileage in electric mode. In parentheses, the reported CO_2 emissions for the vehicles in gCO_2/km.

The reported CO_2 emissions for the vehicles were 112 gCO_2/km for the diesel, 131 gCO_2/km for the gasoline, 101 gCO_2/km for the HEV, 26 gCO_2/km for the PHEV and 0 gCO_2/km for the BEV. The comparison was made for a period of ten years, and it was assumed that the taxation remains unchanged from the tax level in 2017. Additionally, it was assumed that the annual mileage for each vehicle is 18 000 km and that the PHEV covers 55 % of the mileage with the electric powertrain, reflecting the share of electric driving used in the Matero model. The total taxation for a period of ten years is presented in Figure 4. The taxes for the diesel vehicle are 16 800 €, closely followed by 16 300 € for the gasoline vehicle. Compared to the gasoline vehicle, the diesel vehicle has lower car tax due to lower CO_2 emissions, higher vehicle tax due to the powertrain tax and lower excise tax due to lower fuel consumption and lower per liter excise tax. The total tax for the BEV is 3 900 € and 6 700 € for the PHEV. Thus, a BEV benefits from a 12 500 € lower taxation in a ten-year period compared to a gasoline vehicle, and it is questionable if further subsidies are needed.

Similarly, to the Finnish transportation sector, the Norwegian transportation sector is heavily taxed with registration taxes on new vehicles, annual vehicle taxes, taxes on fuels and toll roads. This system has enabled the government to influence the types of vehicles sold, by selectively providing tax exemptions for certain vehicles. [40]. Additionally, there are numerous other local incentives, providing privileges to electric vehicle users as seen in Table 4. The local incentives are mainly exemption from toll road charges, free parking, bus lane access and reduced ferry rates.

Annual benefits from the local incentives for BEVs were valued in 2014 by BEV owners to approximately 1900 €/vehicle. The prices of liquid fuels in Norway are among the highest in Europe, while electricity is cheap and abundant, which further benefits electromobility from a TCO perspective. [25]. The extensive BEV incentives sum up to a large cost for the government, both in the form of direct subsidies and lower tax income. According to Fearnley et al. [40] this can be compensated for by slightly increasing the annual vehicle tax and fuel tax until the electric vehicle technology has reached a stage were the incentives can be decreased. In the same study, it was also concluded that allowing bus lane access is the most cost-efficient incentive, whereas free parking is the least efficient.

Table 4 Incentives, subsidies and policies for BEVs in Norway [41].

Year	Incentive	User benefit
Fiscal incentives - improving price competitiveness of BEVs		
1990	Exemption from registration tax	Registration tax based on emissions. Typical taxes are e.g. vW Up 3000 € and VW Gold 6000-9000 €.
2000	Reduced company car tax	Lower tax on company cars for BEVs
2001	VAT exemption	Exemption from 25 % VAT tax on the sales price excluding the registration tax. Typical VAT on a VW Golf is up to 5000€
1996/2004	Reduced annual vehicle tax	Lowest rate for BEV and FCV (50 € in 2016), while the rate for ICEV range from 350-410 €
Direct user subsidies - reducing operational costs		
1997	Free toll roads	Avoided costs 600-1000 €/year in the Oslo area, and can exceed 2500 €/year in some places
2009	Reduced rates on ferries	Avoided costs for using ferries
2009	Financial support on charging stations	Reduced financial risk for investors in charging stations leading to more charging stations and reduced range anxiety
2011	Financial support on fast charging stations	More fast-charging stations become available
Reduction of time costs giving relative advantages		
1999	Free parking in some locations	Benefit from parking access where parking lots are scarce. Save time looking for parking
2003/2005	Bus lane access	BEV users save time by avoiding congestions

The Norwegian subsidies have clearly been effective in promoting BEV adoption, and a relationship has been found between the number of BEVs per capita in Norwegian municipalities and user value of local incentives. Municipalities with more generous incentives generally have higher amount of BEVs per capita. Incentives that reduce the purchase price with immediate effect compared to local exemptions from costs and taxes are, however, more effective in speeding up the diffusion of BEVs by making the BEV price more competitive compared to ICEVs. [40]. These generous incentives have made Norway the leading BEV market in the world, considering the BEV market penetration in the new registration of vehicles. Some of the incentives have been in place since 1990, but did not have any effect until 2010 when BEVs with Li-Ion batteries started to be manufactured on a large scale by traditional vehicle manufacturers.

Figenbaum et al. [25] state that possible reasons for the slow historical development are customers' current established practices on mobility with vehicles, as well as long vehicle technology development. Transformation of established mobility practices and technology can take decades, as the electric vehicle technology develops in parallel with the existing ICE technology. When the technology is mature, the adoption can be quite rapid as innovators are followed by imitators [9]. Insights into the adoption of EVs and powertrain diffusion into the market are presented in chapter 2.3. New technologies that are costly in the early stages, typically require strong incentives and favorable policies to support the market introduction. In many cases, the provision of information is also important to support new technology and question established practices, e.g. information on TCO as stated previously in this study. [25].

Electric vehicles still need incentives, as characteristics such as range and price are clearly inferior to ICEVs, therefore acting as barriers to EV adoption. In order for a major EV adoption to take place, EV prices need to drop and consumer range anxiety needs to be reduced. Prospects for these two factors are considered in the following chapter. Range anxiety can be reduced by longer EV range, or by faster and more available charging. In this study, the focus is on reduced costs and improved range as a result of battery technology development.

3 Batteries in electric vehicles and battery technology development

The energy storage system in an electric vehicle consists of a combination of components, including the battery cell, cell packaging and a mechanical structure, thermal management systems, cell balancing boards, a battery management system (BMS) and electronic equipment including high-voltage connections, switches and disconnectors. Battery cells are stacked in a module, and several modules together with some of the equipment mentioned above, comprise the battery pack. [42]. It is important to note the difference between battery cells, modules and packs, especially when reporting and analyzing manufacturing costs of batteries. In this study, the differences between battery cells are studied more in detail, as the type of battery cell largely is determining the possible features of the other components, such as cell packaging and thermal management systems.

Battery features vary greatly, depending on what kind of vehicle the battery is used in. HEVs require batteries that can provide high power output when accelerating and enable high-power charging from regenerative breaking, but can manage with low capacities. The power requirement for PHEVs and HEVs are even larger, as they are to be run exclusively on the power from the battery. A HEV battery is typically between 20-60 kW, while it is 40-150 kW for PHEVs and 50-350 kW for BEVs. In general, HEVs operate over a small state of charge (SOC) range, which allows the battery to be used for over 300 000 cycles. SOC is here referring to the operating range of a battery, 100 % being a fully charged battery and 0 % a fully discharged battery. Higher operating ranges enable higher usable capacity. PHEVs typically operate over 80 % of its SOC range, enabling around 4000 cycles over the battery lifetime, while a BEVs typically operate over 90 % of its SOC, enabling 3000-4000 cycles. [43].

One of the most important parameters of battery cells, is the energy density. Some gravimetric and volumetric densities of batteries with different technologies, are presented in Figure 5. Even though the energy densities of batteries have been improving, they are still far from liquid fuels. The volumetric energy density of diesel is approximately 9940 Wh/l and the gravimetric density 13 300 Wh/kg. In the next chapter, battery technology and different battery chemistries are analyzed in detail.

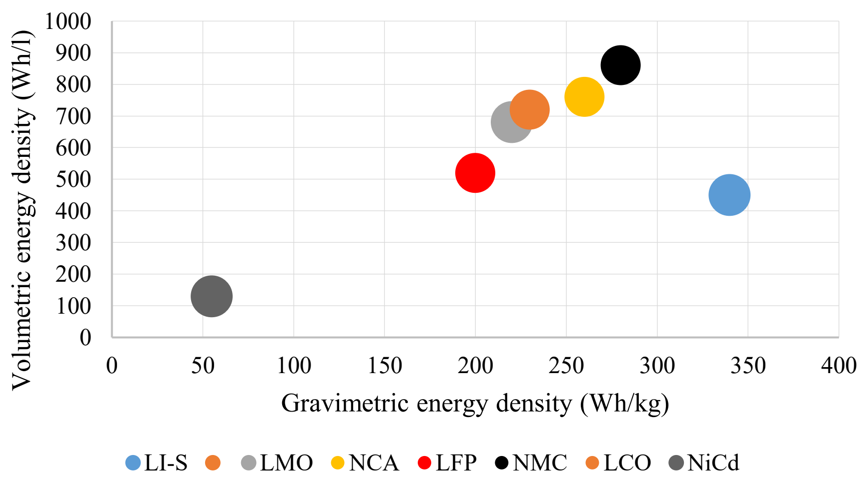

Figure 5 Gravimetric and volumetric density of batteries with different chemistries [44].

3.1 Battery technology and cell design

The battery cells are typically cylindrical, prismatic or pouch cells. Depending on the cell size and chemistry, the capacity can vary significantly, but the typical operating voltage of Li-ion cells is around 2,7-4,2 V [45]. The most common design is the 18650 cylindrical cell, which is 18 mm in diameter and 65 mm in length, directly referring to the name of the cell. A cross-section view of a cylindrical cell is presented in Figure 6. Larger cylindrical cells, which enable higher capacities, are also produced, such as the 2170 cell used in Tesla model 3, with the dimensions 21 mm in diameter and 70 mm in length. Cylindrical cells typically have superior safety features, such as built-in thermal fuses, current interrupt devices and vents. The relatively small cell size also reduces the risk of failure of a single cell, as the potential for cascading failure propagation is reduced. The large-scale manufacturing of cylindrical cells has enabled cost-reductions, and made cylindrical cells a very cost-efficient alternative. A drawback is the low capacity, which ranges from 2-3,5 Ah, which makes larger capacity EV batteries require thousands of cells. [43].

Prismatic cells have a higher capacity, ranging from 4-250 Ah, as a result of the larger cell size. The larger cell size, allows for higher battery capacity density, as a proportionally larger share of the material is active material, and not casing material [46]. The anode and cathode can be packed in a Z-fold, stacked or a roll design, and is typically enclosed in an aluminum or plastic case. The Z-fold design principle is based on a continuous folding of the anode, cathode and separator in one run to form a cell. The stacked design incorporates separate pieces of anode, cathode and separator stacked on the top of each other. The cells are then connected to each other to transport the current to the terminals. The roll design is similar to that of the cylindrical cell, but the roll is fit into the prismatic case format. A problem with higher cell capacity, is the risk of cascading failure propagation from the failure of a single cell.

The third cell packaging type is pouch cells, also referred to as polymer cells or laminar cells. These are based on a Z-fold or a stacked design of the anode, cathode and separator, and enclosed in an aluminum laminate pouch. The pouch cell enables various shapes and designs, as well as high energy density from the large cells and low share of required enclosing material. The soft aluminum laminate pouch enclosing increases the risk of physical damage, and an outer casing is often needed. The risk of physical damage is especially relevant in EV applications, where batteries are exposed to vibrations and possible penetration in accidents. Pouch cells suffer from the lack of integrated safety features, such as thermal fuses, current interrupt devices and vents. Similar to the prismatic cell, pouch cells have high capacities, ranging from 20-100 Ah. The large capacity of pouch cells, reduces the number of required cells, but also increases the risk of cascading failure propagation. [43].

Irrespective of the cell design, the most successful battery chemistry has so far been lithium-ion. The lithium-ion technology benefits from higher energy density (Wh/kg) and higher power density (W/kg) compared to other technologies. Supercapacitors are able to provide higher power density, but they suffer from low energy density. Certain fundamental characteristics make lithium a favorable element in batteries. The reduction potential of lithium is the lowest of all elements, which enables an as high as possible cell potential. It is also the third lightest element, which allows for a high gravimetric capacity and a high power density. The volumetric capacity and power density are also high, since the lithium ion has the smallest radius of all single charged elements.

Cations with multiple charges could provide higher charge capacity per ion, but multiple charge ions have lower mobility. This slows down the charge diffusion in the electrode, which reduces the battery's rate capability. [47]. Here the rate capability refers to the maximum charge and discharge rate. Considering battery degradation, both cyclical and calendrical aging, the lithium-ion batteries outperform other technologies. Benefits of lithium-ion chemistry are also a suitable operating temperature range, high cell voltage and good charge retainment. In general, lithium-ion batteries provide the best combination of energy density, power density, lifetime, safety and costs, and are thus the most promising technology for electric vehicle applications. [48].

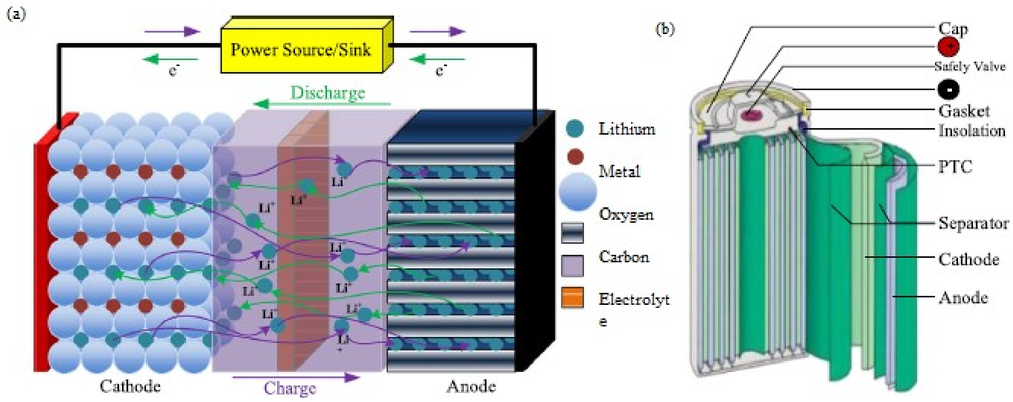

Figure 6 Basic principle of a Li-ion battery during charge and discharge (a) and a cross section view of a cylindrical battery (b). Modified from Hannan et al. [49].

Looking in detail at the battery cell, it consists of four major components, which are the cathode, anode, electrolyte and separator. The battery operates by the reversible inclusion or insertion of ions into the layered structure of the cathode and anode, a process called reversible intercalation. [50]. The basic operating principle is illustrated in Figure 6. Lithium ions are displaced between the cathode and anode, while electrons flow through the external circuit. During charging, ions diffuse into the anode, which is the negative electrode. Similarly, the ions diffuse into the cathode during discharge. The electrolyte enables the ions move, while the separator prevents contact between the anode and cathode which would result in short-circuit [51]. Organic electrolytes with lithium salt solutions are mostly used, as the electrolyte has to tolerate high voltages of 3-4 V [52]. A typical electrolyte in EV applications is $LiPF_6$ in a carbonate solution [45].

3.2 Battery cathode materials

Cathode materials for intercalation lithium-ion batteries are chalcogenides, lithium-containing transition metal oxides and polyanion compounds. The most typical cathode material of these three, are the transition metal oxides, which have a crystal structure that enables lithium-ions to diffuse freely through the structure. Typical transition metal oxides are Lithium Cobalt Oxide (LCO) $LiCoO_2$, Lithium Manganese Oxide (LMO) $LiMn_2O_4$, Lithium Nickel Manganese Cobalt Oxide $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC) and Lithium Nickel Cobalt Aluminum Oxide (NCA) $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$. When commercial production of lithium-ion batteries started, LCO was the dominating cathode material. [50]. Currently NCA, LMO and NMC are the dominating cathode materials [46].

A great amount of research has been conducted related to the improvement of the lithium-ion battery cathode. Cathodes with higher rate capability, increased charge capacity and high voltage could improve the power and energy densities of the batteries. LCO was used in the first commercially available transition metal oxide cathode, introduced by SONY. The major drawbacks with LCO batteries are high material cost and low thermal stability. Low thermal stability refers to the exothermic release of oxygen at hot temperatures at the cathode, which can result in a thermal runaway reaction and the cell can burst into flames. LCO have very low thermal stability compared to other commercial transition metal cathode materials, and thermal runaway reactions occur at temperatures around 200 °C. Cathodes made of $LiNiO_2$ (LNO) have a very similar gravimetric capacity and structure as LCO, but the nickel-based materials in the LNO cathode are significantly cheaper than cobalt-based materials. Pure LNO cathodes suffer from nickel ions (Ni^{2+}) occupying the lithium ion (Li^+) sites, blocking diffusion pathways for the lithium ions.

Thermal stability is also a problem of LNO cathodes, but it can be diminished by adding Mg and Al doping. The electrochemical performance is also improved by Al doping, and replacing Ni with Co reduces cationic disorder. Utilizing these materials for doping, the $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA) has been found and used in commercial applications, such as Tesla electric vehicles. NCA has a relatively long calendar life, but suffers from fast fading capacity at temperatures in the range 40-70 °C. The fading capacity is a result of microcrack growth and solid electrolyte interface growth. Another element used in cathodes is Mn, as it is cheaper and less toxic than Ni and Co. Mn has been used in $LiNi_{0.5}Mn_{0.5}O_2$ cathodes. The Ni doping in the $LiNi_{0.5}Mn_{0.5}O_2$ cathode enables higher Li-ion extraction capacity, which increases the capacity of the battery. However, these cathodes suffer from structural changes during charging and discharging and Mn dissolution in the electrolyte. An addition of Co improves the structural stability. As a result, the NMC cathode with Ni, Mn and Co doping has been widely commercialized and successful. [47].

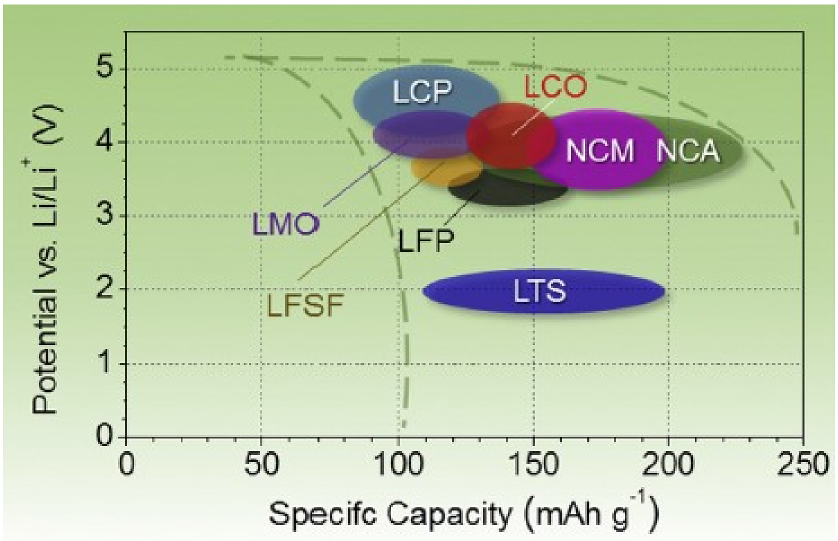

Figure 7 Typical intercalation-type cathode materials and their approximate discharge potentials and specific capacity [47].

Apart from transition metal oxides, polyanion compounds are also used as cathode material. Polyanion compounds used in lithium-ion batteries are e.g. $LiFePO_4$ (LFP), $LiMnPO_4$ (LMP) and $LiFeSO_4F$ (LFSF), with the respective polyanions PO_4^{3-} and SO_4^{3}.

A benefit with the polyanion compound cathode is the increased redox potential and stabilized structure, as the polyanions occupy lattice positions. LFP and LMP have an olivine structure, whereas LFSF has a favorite structure. LFP is the most common polyanion and has outstanding stability, and has been installed in the Mercedes S550 PHEV [46]. The drawbacks of polyanion compound cathodes are low electric conductivity and low potential. LMP has higher potential leading to higher specific energy, but suffers from even lower conductivity. [47].

3.3 Battery anode materials

The battery cell anode is almost exclusively made of carbon, normally in the form of graphite. The most common type of graphite is modified natural graphite. Natural graphite has a high reactivity with the electrolyte, and it has to be modified prior to use. Natural graphite is the cheapest type of graphite, and carbon layer coating of natural graphite has enabled it to be used as anode material. Hard carbon is also used as anode material, particularly in HEV applications. Graphite is typically preferred over hard carbon, as it has a broader and flatter discharge curve than hard carbon. [47]. There is very little room for improvement in the graphite anode capacity, and the research has turned to new materials. Promising materials at a well-developed stage are alloying materials and metal oxides.

Alloying materials are referred to as elements, which electrochemically form compound phases with lithium. These materials provide much higher volumetric and gravimetric capacity than graphite, which enable improved capacities. Theoretical volumetric and gravimetric capacities of graphite, lithium and some typical alloys are presented in Figure 8. The alloying materials suffer from extreme volume change during lithiation and delithiation, which here refers to discharging and discharging. A changing volume damages the anode by causing particle fracture and loss of electrical contact. [50]. The volume change can also damage the solid electrolyte interface (SEI) on the anode. The solid electrolyte interface works as a protective layer and prevents continuous electrolyte decomposition and loss of lithium inventory, while still allowing Li-ions to pass the interface. Therefore, the SEI is desirable in the first operating cycles of the battery cell, but if the SEI layer continues to grow, it consumes lithium and the battery cell performance is reduced. Surface layers can also form on the cathode but are typically much thinner. [51].

Batteries with anodes that have large volume change typically suffer from high impedance and loss of active material, which leads to short cycle life. The volume change of graphite is 10 %, and in recent applications, a thin layer of amorphous carbon has been applied on graphitic carbon to protect it from the electrolyte. The volume change of e.g. Silicon (Si) is 270 % and Tin (Sn) is 255 %, which is why it is challenging to use them as anode material, even though they would provide higher capacities. [47]. To overcome the problems with volume change, the alloying materials can be used as a carbon composite, or by forming the material in nanoparticles. Forming the materials into nanoparticles reduces the impact of volume change as the particles have a smaller radius. [50].

Silicon is one of the alloying materials that have received the most attention. Benefits with Silicon is the high capacity, chemical stability, non-toxicity, low cost and abundance. Tin is also interesting due to its higher electrical conductivity, but a drawback is the lower gravimetric capacity. Tin is also prone to fracturing during volume change, even when the size is reduced to the 10 nm range. Similarly, Aluminum have problems with fracturing even in the nano-level. Typical anode alloying materials like Zink (Zn), Cadmium

(Cd) and lead (Pb) suffer from low gravimetric capacity even though the volumetric capacity is high. The use of Germanium and Gallium is typically discarded due to the high cost of the materials. [47].

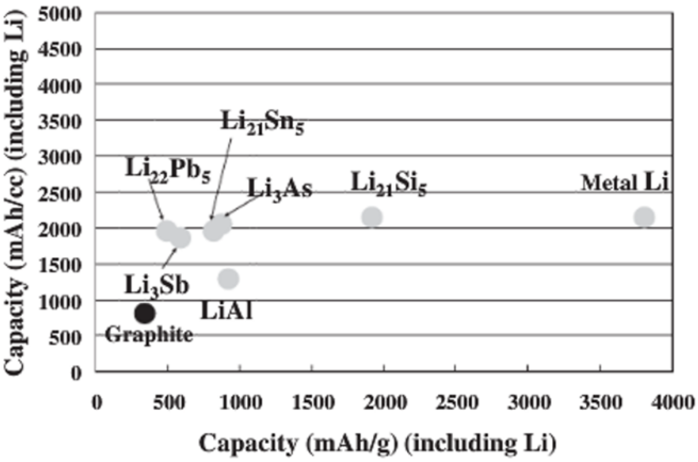

Figure 8 Theoretical discharge capacities of metal alloy anodes [50].

An anode material that has been successfully commercialized is lithium titanium oxide (LTO). LTO batteries have superior thermal stability, high equilibrium potential, very high cycle life and high rate capability. Additionally, the volume change during lithiation and delitihiation is only 0,2 %, which is one of the factors that make LTO batteries last for last for tens of thousands of charging cycles. Drawbacks with LTO batteries are low capacity, 175 mAh/g and 600 mAh/cm^3, and high cost of titanium. Due to the high rate capability and high cycle life, the batteries are often used in high power applications. [47]. The Honda Fit EV was using LTO batteries, but currently the interest in EV applications has decreased [46].

To avoid the problem with battery degradation as a result of liquid electrolyte decomposition, solid electrolytes for Li-ion batteries are considered. However, according to Kurzweil [53] battery cells with solid electrolytes are not expected to be commercialized and produced in the coming decade. Solid-state electrolytes provide high electrochemical and thermal stability, as well as improved safety due to the nonflammable electrolyte and no risk of electrolyte leakage. The solid-state electrolytes can also enable batteries with higher energy density and improve the cell design through more efficient cell packaging and thin-film applications. High cycle life is another major advantage, which is partly attributed to no dissolution of electrolyte at the electrode. [54]. In general, the solid-state electrolytes suffer from poor electric conductivity, and the electrode-electrolyte interface needs to be improved for a wide commercialization of batteries with solid-state electrolytes. Solid-state electrolytes can be gel polymer electrolytes and ceramic or glass electrolytes. The gel polymer electrolytes have already been commercialized, whereas ceramic and glass electrolytes are still in a development and research stage. [53].

Looking beyond lithium-ion batteries, batteries with conversion type cathodes are possible successors. Conversion type cathodes can e.g. be made of compounds like metal fluorides and chloride, sulphur, lithium sulfide, selenium, tellurium or iodine. Conversion type electrodes undergo solid-state redox reactions during lithiation and delithiation, in contrast to lithium-ion batteries, where lithium ions are stored in the electrodes through intercalation. As a part of the redox reaction, chemical bonds are broken and recombined and the crystalline structure of the electrodes are changed. Lithium-sulphur (Li-S) batteries have attracted a lot of attention, as sulphur has a superior theoretical capacity of 1675 mAh/g, compared to 274 mAh/g of LCO. Additionally, S is abundant in the Eart's crust and it is thus a low-cost material. A major challenge with Li-S batteries is the fact that S is an electrical insulator and needs to be incorporated in a conductive matrix that enables the diffusion of ions and electrons. This conducting structure is typically made of carbon or graphite. Drawbacks with Li-S batteries are also low electrical conductivity, low potential vs. Li/Li^+ and dissolution of intermediate polysulfide reaction products in the electrolyte. The volume expansion of S during lithiation and delithiation is 80 %, which also poses a challenge of fracturing and loss of electrical contact. [47].

Furthermore, several other battery technologies do also exist, that could contribute to an improved capacity and reduced cost of battery cells. All the technologies and characteristics described in this chapter highlights the fact that there are many possible improvements to be made, and the current development is going to a variety of different directions. As a result, it is reasonable to think that these improvements will continue to drive down the cost, which is further elaborated in chapter 2.6.

3.4 Battery lifetime and temperature dependency

Directly related to the lifetime of an electric vehicle, is the lifetime of the battery. In order for electric vehicles to replace conventional ICE vehicles, they should be able to provide a comparable lifetime, which is mainly dependent on the lifetime of the battery. The battery lifetime is often considered to be an uncertain parameter, which is why a closer look at the phenomenon is needed. Li-ion batteries show decreasing performance over time, which can be described as reduced capacity and lower power output. Typically, the performance of Li-ion batteries deteriorates slower than the performance of other batteries, which make Li-ion a preferred chemistry. [45].

The decreasing performance can be divided into cycle aging and calendar aging. Cycle aging refers to aging mechanisms related to charge and discharge of the battery, while calendar aging refers to the aging during nonoperating conditions. Cycle lifetime is measured in how many charge and discharge cycles the battery can withstand, typical values ranging from 2000 – 5000 cycles for batteries in EV applications. [45]. End of life can be described as the moment when the battery cannot be used for a certain application anymore. In EV applications, the battery is considered to have reached the end of its life, when the capacity or power output has decreased to 80 % of its initial value. Capacity loss is typically the more important factor, as power output mostly is significantly higher than required. However, for HEVs the power output, or rate capability, is often the limiting factor. [51].

A deteriorating capacity reduces the maximal amount of energy stored in the battery, and thus also the maximal range of the EV. A large number of different aging mechanisms can explain the deteriorating battery performance. The most relevant in EV applications are transformations of active material in the electrodes, the electrolyte and the interface between them. Aging mechanisms with the most impact are surface film formation on the electrodes, structural material changes, mechanical changes and parasitic reactions. Surface film formation refers to the formation of solid electrolyte interface and lithium plating. Structural changes are e.g. cation disorder and phase transition, while mechanical changes can be particle cracking, gas formation and loss of electric contact, often related to the volume change of the electrode materials. Parasitic reactions refer to e.g. corrosion on the current collectors. Solid electrolyte formation around the anode and phase transition in the cathode are two main mechanisms related to loss of battery capacity. A reduced power output is mainly caused by increasing impedance, which often is a result of the reduced accessible surface area from SEI formation and contact loss due to the volume change of electrodes [51]. The increased impedance causes lower battery efficiency and increased heat production. The heat production can be described as ohmic heating, that is, the product of the resistance and the square of the current. [45]. For a typical BEV battery, currents around 300 A are not unusual, and with so high currents an increased impedance is a major drawback [43].

The speed of battery aging is strongly dependent on certain operating conditions, such as temperature, SOC, and cycling rate. Accelerated aging at high temperatures is not surprising, as many of the aging mechanisms are thermally activated. Almost all aging mechanisms are accelerated at high temperatures, both during storage and cycling. These are e.g. self-discharge of the anode, loss of lithium due to SEI formation and dissolution, surface film formation at the cathode, electrolyte oxidation and cathode transition metal dissolution. [45]. High temperatures in combination with extreme SOC values can cause dissolution of active cathode material into the electrolyte and eventually on the anode. Low temperatures, can on the other hand also be problematic. The risk of lithium plating during fast-charging is, for example, significantly increased at temperatures below 20 °C. Extreme SOC values can also cause particle fracture and loss of electrical contact, due to the volume change of the electrodes as a result of Li-ion loading. Aging due to overcharging is also related to the SOC. Overcharging the battery by allowing a too high terminal voltage, can result in metallic lithium deposits on the anode. [51].

To assess the impact of temperature on battery lifetime, Pesaran [55] studied the operating temperature of a variety of batteries and suggested an operating range between 15 °C and 35 °C. Nelson et al. [42] consider temperatures above 40 °C to accelerate the degradation reactions. Figure 9 illustrates the suitable operating range of Li-ion batteries and mechanisms at lower and higher temperatures. To maintain suitable operating conditions, modern battery systems in EVs are equipped with advanced thermal management systems. This system is able to heat up the battery during cold winter days and cool the battery when it operates at high loads in high temperatures. This way, the battery temperature can be maintained at an optimal operating temperature, and both sufficient power at low temperatures and operation without accelerated degradation at higher temperatures can be achieved. [42].

Modern thermal management systems can use air or a liquid as the cooling medium. Liquid cooling systems transport heat more efficiently, but are often more expensive. In liquid cooling systems, Aluminum cooling plates are often used in the combination with cooling lines, where the liquid can flow. Batteries with cylindrical cells have more space between the cells and do often require less cooling, which is why air cooling systems might be sufficient. [43]. Naturally, the thermal management system requires energy, and this will affect the range of the vehicle.

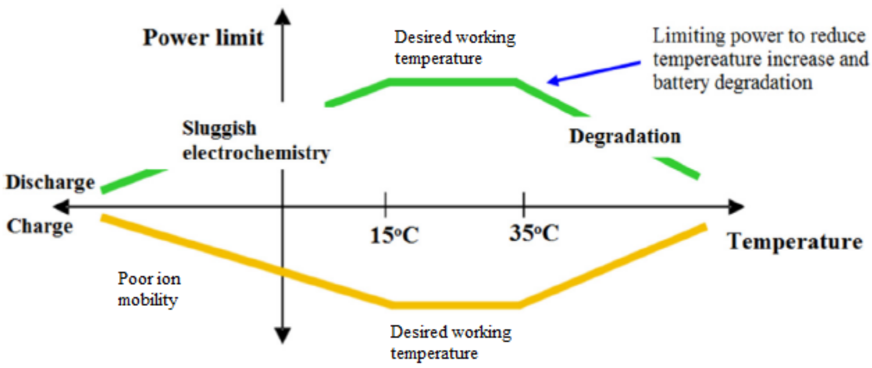

Figure 9 Impact of temperature on battery operation and degradation. Modified from Pesaran [55].

Sufficient thermal management for each cell is often challenging in an EV battery pack, due to the large number of cells in a pack. Lithium-ion battery cells typically operate in the voltage range of 2,7 - 4,2 V, depending on the electrode materials. To reach sufficient capacity and voltage, it is not unusual that up 100 cells are connected in series to provide a voltage between 200 V and 400 V. Maintaining a long lifetime requires that the lifetime of every single cell is maintained. As the capacity of a battery consisting of cells connected in series, is determined by the cell with the lowest capacity, each cell needs to operate under suitable operating conditions to provide long lifetime. Therefore, a battery management systems optimizing the operation of the battery is also required. [45].

As the operating conditions and aging mechanisms affecting battery degradation are known, a calculation example can help to explain the battery lifetime. It was previously mentioned that a typical cycle life of batteries in EV applications is between 2000 and 5000 cycles [45]. Considering a BEV with a range of 100 km and a battery cycle life of 4000 cycles, the total possible mileage would be 400 000 km. Assuming an average mileage of 20 000 km for the BEV, the lifetime would be 20 years. Thus, it can be concluded that batteries in electric vehicles can provide a sufficient lifetime.

3.5 Cold weather performance of battery electric vehicles

Since Finland, Sweden and Norway have unusually cold climate, the battery performance at cold temperatures is very important for EV adoption in the respective countries. BEVs are known to have shorter operating ranges at cold temperatures, and the reason behind this is explained in this section. However, conventional ICE vehicles do also have a battery, which provides energy to start the engine. This battery mainly needs to provide a short peak current, and is thus, a less critical part than the EV battery and therefore the impact of cold temperatures is not as significant. Wang et al. [56] provide several examples of how much the EV range decreases in sub-zero temperatures. The decreased range varies depending on battery chemistries and usage patterns, but a 30-40 % decrease is not uncommon.

Delos Reyes et al. [57] tested the range of a Nissan Leaf and two Mitsubishi i-MiEVs in temperatures ranging from +28 °C to -26 °C. All vehicles were of model year 2012, and utilizing available heating equipment to maintain a comfortable cabin temperature around +21 °C. Air conditioning was only used in special cases, and the results of tests where air conditioning was used, were treated separately. The tests were performed during a period from June 2013 to March 2014 in and close to the urban area of Winnipeg, Canada. A linear correlation between range and temperature was noticed in the range of +20 °C to -

5 °C, so that the available range decreases with lower temperatures. The maximum range of the Leaf was noted to be roughly 163 km in optimal operating conditions, while the minimum range was around 52 km. The maximum range of the i-MiEVs was 130 km and the minimum recorded range was around 44 km. The minimum ranges were all recorded in temperatures lower than -15 °C, and the range decrease in cold temperatures can be concluded to be over 65 % in the worst conditions.

All vehicles experience some operational problems with cold temperatures, and the performance of EVs in cold weather is often considered a barrier to EV adoption. In vehicles, cold ambient temperatures particularly affect all moving parts, battery chemistry and the motion resistance. All this result in the fact that vehicles tend to have a lower range when operating in cold temperatures. Additionally, air resistance is higher at cold temperatures. For conventional ICE vehicles with high ranges, this is not a big issue. However, for EVs with significantly lower ranges, the difference can be very important. During cold start conditions, conventional ICE vehicles experience problems with cold lubrication oil, condensate freezing on moving parts and thermal stress on materials. EVs have significantly less moving parts, and the parts are mostly separated by air, which means that there are fewer parts that need lubrication, which makes the EV more suitable for operation in cold ambient temperatures from that perspective. However, that benefit is overrun by the reduced range and energy demand for heating. [57].

In a BEV, the cabin is heated by resistive heaters or heat pumps. The electricity for this is taken from the same battery that is used to drive the car forward. This directly affects the driving range. In ICE-vehicles the chemical energy stored in the fuel is turned into heat, which in turn is converted into mechanical energy. The efficiency of this process is typically around 20-25 %, and plenty of waste heat is produced that can be used to heat up the cabin and the engine. In a BEV, the chemical energy stored in the battery is converted into electricity which is used by the electric motor to produce mechanical energy. The efficiency of the electric motor is much higher and waste heat for cabin heating is not provided. Similarly, when ambient temperature is high, energy is required for air conditioning to provide a comfortable ride in the vehicle. For ICE-vehicles, an increase in fuel consumption is noted when the air conditioning is used.

For EVs air conditioning requires energy from the battery, which leads to a lower driving range. There is no solution to the energy requirement for heating and cooling of the cabin in electric vehicles. Still, the efficiency of heating and cooling appliances is continuously increasing, and there are simple and practical ways of reducing the effect of cabin heating on driving range. If the car is plugged into the electrical grid it can be preheated prior to use. Similarly, at high ambient temperatures, the cabin can be cooled using electricity straight from the grid. In cold climate preheating of the engine is already widely in use, so this would not cause a major change for the customers. Apart from the heating of the cabin, energy is also needed for thermal management of the battery as described in the previous chapter. The battery thermal management is also needed at high temperatures, to maintain the battery temperature in a suitable operating range. [58].

Further reducing the range of EVs at sub-zero conditions, is the poor performance of Li-ion batteries in cold conditions. This is predominantly a result of lower ionic mobility in the battery cells. The lower ionic mobility is caused by increased charge transfer resistance on the interface between the electrolyte and the electrode, as well as lower conductivity of the electrolyte, electrode and the SEI. As the temperature decreases the mobility is lowered, less thermal energy is available in the electrolyte and ions and molecules require more energy to overcome their mutual interactions or friction. [59]. A decline in the solid state diffusivity and polarization of graphite anodes are also factors causing a lower performance in cold temperatures [56]. Features like separator porosity and electrode thickness are also affecting the performance in cold temperature [58]. As the conductivity of the electrolyte decreases at low temperatures and causes a higher internal resistance, electrolytes with low freezing points and high conductivity are suitable for battery operations. A low freezing point is relevant as temperatures below -30 °C can cause freezing and dissolution of the typical commercial electrolyte $LiPF_6$. The battery performance can also be increased by introducing materials that cause a lower charge-transfer resistance between the electrolyte and the electrodes, and electrode materials with lower ion diffusion resistance. [59].

The decreasing battery performance in cold conditions is a combination of many factors, and it is often challenging to determine which factor has the largest impact. Jaguemont et al. [58] state that poor diffusion of lithium ions in the carbon anode is the main reason for poor performance in cold operating conditions. Lithium-ion diffusivity has been observed to be significantly lower in graphite anodes of discharged batteries than in graphite anodes of charged batteries. That is, the diffusivity is lower in delithiated graphite compared to lithiated graphite. This is one explanation for problems with charging cold empty batteries, which has been proven much more problematic than discharging cold batteries. To reduce the effect of poor battery performance at low temperatures without having to change the battery chemistry, the battery can be heated. This can either be done with the thermal management system, or by the self-heating ability of batteries.

Heating with the thermal management system requires significant amounts of energy, which make the self-heating ability of batteries an attractive solution. The self-heating effect is always present in Li-ion batteries, as a result of ohmic heating due to the internal resistance of the battery. However, the effect of ohmic heating is not sufficiently fast and powerful, especially considering the negative impact on battery lifetime from operating in cold temperatures. Zhang et al. [60] present a self-heating lithium-ion battery structure utilizing a two-sheet nickel foil embedded in the Li-ion cell, which provides rapid and efficient self-heating abilities. The method has been proven to heat up batteries from -20 ˚C to 0 ˚C in 12,5 seconds consuming only 2,9 % of the battery capacity, and also effectively support a long battery lifetime. These kinds of innovations are expected to reduce the impact of poor battery performance in cold conditions.

4 Prospects for falling electric vehicle battery prices

As previously described, the high battery price and poor range are perhaps the most significant barriers to adoption of electric vehicles. In order to create reasonable scenarios for powertrain development in Finland, Sweden and Norway, the prospects for falling battery prices are therefore assessed. The electric vehicle manufacturers are constantly working to overcome the barriers, by increasing the electric range and reducing the costs at the same time. These two factors are closely linked to each other, and rely on the development of battery technology and battery production costs. Cheaper batteries enable higher battery capacity which leads to improved ranges. Similarly, higher battery energy density enables smaller and lighter batteries which result in higher efficiency and improved range due to the lighter weight. Eventually, the current characteristics and prices of batteries, are not as important as future characteristics and prices. The speed of development is rapid, and there are a lot of possible improvements, which was highlighted earlier in this study. Thus, arguments that electric vehicles are expensive and have insufficient range, might not be relevant in the coming years.

Recently automotive manufacturers are bringing small and medium-sized BEVs, with real-world driving electric ranges exceeding 300 km to the market. These are vehicles like Tesla Model 3, Opel Ampera-e and the new generation Nissan Leaf. These vehicles are certainly reducing the range anxiety for BEV owners, as the previous versions of electric vehicles typically were able to cover less than 200 km. The trend with increased electric vehicle range is also clear when considering announced future models. Improved vehicle efficiency, as a result of improvements in powertrain efficiency, power electronics, aerodynamics and lightweighting technologies, is one of the factors enabling the longer electric ranges. [61]. However, battery packs with higher capacities are the main explanation of the increased range. The 2015 Nissan Leaf has a 24 kWh battery, whereas the 2018 Nissan Leaf comes with a 40 kWh battery [62], the new Opel Ampera-e with a 60 kWh battery [63] and the Tesla model 3 with either a 50 kWh or a 75 kWh battery [64].

The increased battery capacity is supported by falling battery production costs and increased energy density. Battery prices are in a key position for a widespread diffusion of electric vehicles. Battery technology and battery manufacturing methods have been improving dramatically over the last years, both concerning costs and energy density. The prospects for a further decreasing battery price and improved energy density are also encouraging, both concerning publicly communicated targets as well as the historical development. [1]. The electric vehicle market has still been so small, that a few manufacturers and even a few vehicle models have been able to drive the development of different battery cell technologies.

Currently, around half of the storage capacity consists of cylindrical lithium-ion cells and the other half of prismatic cells. The most common battery chemistry on the U.S. market is currently Lithium Nickel Cobalt Aluminum Oxide (NCA), which comprises roughly half of the EV storage capacity. The other chemistries, accounting for approximately a quarter each, are Lithium Manganese Oxide (LMO) and Lithium Nickel Manganese). On the U.S. markets, NCA cells are dominating the BEV storage capacity, largely due to the large sales of Tesla Model S with batteries of 75 kWh or 90 kWh. BEVs using NMC cells are e.g. BMWi3, VW e-Golf and Fiat 500e, whereas Nissan Leaf uses LMO cells. The

PHEV market has been dominated by the Chevrolet Volt, which comes with a combination of LMO-NMC battery. The PHEV Volt comes with a larger than average 16,5 kWh storage capacity, and thus the LMO-NMC chemistry has dominated the PHEVs. [65].

4.1 Cost structure of different battery technologies

Ciez and Whitacre [46] studied the cost structure of lithium-ion cells used in the EV market. Costs related to battery cell characteristics like cell dimensions, electrode thickness, chemistries and production volumes were examined. Recently, the battery pack size has increased rapidly and cylindrical lithium-ion cells have been used in EV applications. The typical cylindrical cell is the 18650, with a diameter of 18 mm and height of 65 mm. These cells are used in Tesla Model S and Model X, whereas Model 3 uses larger 2170 cells with a diameter of 21 mm and height of 70 mm. In the study, manufacturing costs of 18650 cells with electrodes of 70 µm and an annual production capacity of 2 GWh, were examined. It was concluded that the per kWh costs of cylindrical LMO cells are significantly higher than the other chemistries. The amount of LMO cells needed to produce 2 GWh of storage capacity are approximately double the amount of NCA and NCM cells, which increases the cost even though the active material costs are lower. The LMO cells have lower specific energy, and the cylindrical format is too small to support a sufficient electrode thickness. For the other chemistries, increased electrode thickness leads to lower per kWh costs, as the active material occupies a larger volume of the cell in proportion to separators and current collectors. Additionally, larger cell size and increased annual production do also contribute to lower battery costs.

A comparison of productions costs of baseline 18650 cells and optimistic 20720 cells with 100 µm electrodes, was also performed by Ciez and Whitacre [46]. The material costs, accounting for around 40 % of the total costs, stands out as the clearly most significant cost factor. Other major cost factors are equipment costs and labor costs. The costs, reported separately for LMO, NCA and NMC chemistries, were also compared to results for prismatic cells by the cost model BatPaC developed by Argonne National Laboratory [66]. The results are shown in Figure 10. Breaking down the material costs for the cylindrical cells, close to half of the costs are related to hardware, including terminal assemblies and the container. In the study, it is stated that it is unlikely that the cost of these components would fall significantly from large-scale production, as they have been mass-produced for decades. Comparing the cylindrical NCA and NMC cells, the production cost of NMC cells are slightly lower. The prismatic cells are considered to be cheaper for all battery chemistries, as seen in Figure 10. This is due to the fact that larger prismatic cells allow for thicker electrodes, which reduces per kWh hardware costs.

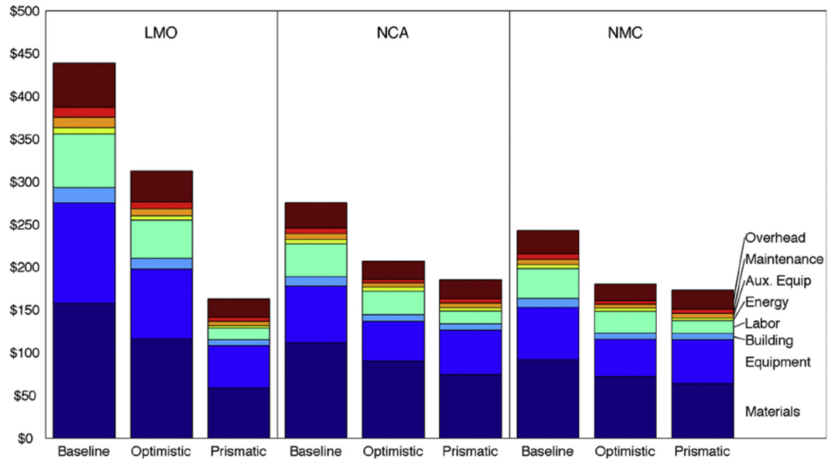

Figure 10 Cost structure per kWh of baseline 18650 cylindrical cells, optimistic 20720 cylindrical cells and BatPac prismatic cells [46].

A higher cost of lithium is often mentioned to upend the decreasing price of batteries, but it is worth noticing that only a small share of the costs is related to lithium. Of the material costs, the costs for cathode precursors typically comprise around 20 % or more, and play an even larger role as the cell size increase. In cathode production, the active material is taken from cathode precursors in a chemical bonding process. Subsequently, the synthesized active materials are adjusted and coated onto the electrode current collector. In cathode production, the majority of the costs are related to the cost of processing and other materials than lithium. [47]. For the baseline 18650 cells, lithium carbonate accounts for roughly 2 % of the total costs. In the optimistic 20720 the cost of lithium carbonate is around 3 % of the total cost. The cost of lithium carbonate is considered to be $ 7,50/kg, but even when the price is increased to $ 25/kg, the share of the total costs never exceed 10 %. [65]. Based on these results, it evident that the effect on battery costs from fluctuations in lithium price is limited.

4.2 Falling battery prices due to industrial learning and economies of scale

Large-scale manufacturers like Tesla and Panasonic or GM and LG Chem have announced costs of battery packs to be in the range of $ 180/kWh to $ 200/kWh. These estimates are significantly lower than other estimates, which typically are around $ 300/kWh and higher [61]. This illustrates the uncertainty related to battery production costs, and in general the cost structure of electric vehicles, as previously mentioned in chapter 2.2. Variation in cost estimates is also a result of the cost estimates referring to battery cells, modules and complete packs. These should be clearly distinguished, as the per unit cost of a complete battery pack naturally is higher than a battery cell. The module includes e.g. module terminals and the module casing, while the battery pack includes e.g. battery terminals, bus bars and battery jackets. Equipment needed for the integration of the battery into the vehicle, such as current and voltage sensing, module controls, automatic battery disconnectors and manual disconnectors, might also be included in the battery pack cost estimates. Depending on what specific equipment battery cost estimates refer to, the cost difference can be even as high as 25 %. [42].

Figure 11 presents assessments on production costs and energy density by the US Department of Energy. These estimates are on production costs of high-volume commercial-scale production of new technologies, that currently are being researched. In this case, the cost-estimates are based on an advanced lithium-ion technology with silicon alloy-composite anode referring to a battery pack that can deliver 320 km of electric range. The blue dotted line illustrates the fall in costs of PHEV battery costs assessed by the US Department of Energy. Between 2009 and 2015, the price fell from $ 930/kWh to $ 268/kWh. In the same time, the volumetric energy density increased approximately four times. In 2016 the assessment was changed to focus on batteries for BEVs instead of PHEVs. Tesla has the most optimistic battery production cost target of $ 100/kWh in 2020, GM has set the same target for 2022 and the US Department of Energy has set a target on $ 125/kWh. [8].

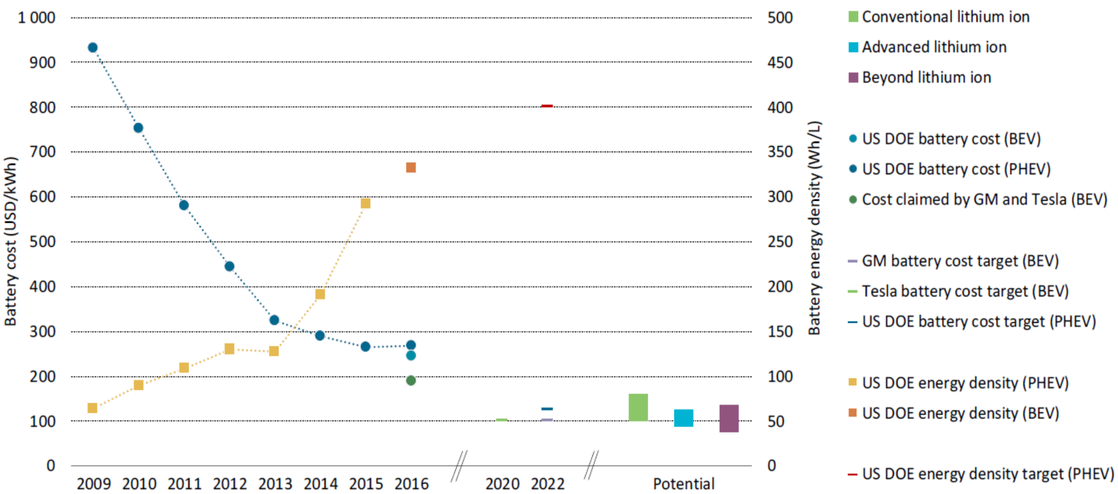

Figure 11 EV battery price and energy density development including targets for the future [8].

Engineering advances in battery pack, cell and electrode design as well as economies of scale and industrial learning are generally considered as possible ways of achieving lower battery prices. Introduction of new improved cathode, anode and electrolyte materials are also expected to reduce the cost of batteries, by improving their performance. [46], [66], [67]. Quantifying the effect of these parameters is a challenging task, especially considering the poor information on battery manufacturing costs, which is depicted by the wide range of battery cost estimates. Nykvist and Nilsson [30] assessed over 80 cost estimates including peer-reviewed international scientific journals, estimates by consultancy agencies, industry analysts and industry representatives. The estimates were from 2007-2014, and only high capacity Li-ion battery packs were included, excluding all battery packs used in hybrid applications. A total of 85 data points was used for historical values and 37 data points for future cost estimates. The yellow triangles in Figure 12 represents the future cost estimates, and the other data points are historical values.

Historical values were separated into values for market leaders and other manufacturers, as the possibilities for cost reductions are different for these two groups. It was noted that the cost of battery packs decreased with 14 ± 6 % annually between 2007 and 2014, combining all data points. This gives a view on the cost reductions for the whole industry. Considering only the market leaders, the annual cost reduction was 8 ± 8 %. As the whole industry includes many manufacturers with low production volumes and immature technologies, it is reasonable to exclude these and focus on the market leaders when evaluating the prospects for falling battery prices. Assuming that the annual cost reductions would continue to be 8 % for market leaders after 2014 and that the costs in 2014 was $ 300/kWh, the cost of battery packs would be $ 180/kWh in 2020 and $ 120/kWh in 2025. With a euro to dollar exchange rate of 1,18 the costs in euro would approximately be 150 €/kWh in 2020 and 100 €/kWh in 2025.

Learning rates for battery pack manufacturing were also estimated by Nykvist and Nilsson [30], including 95 % confidence intervals derived with a two-tailed t-test. Learning rates refer to the reduction in costs from a doubling in cumulative production. The cumulative battery capacity was assumed to have grown by more than 100 % each year since 2011. The learning rate using all data points, was found to be 9 %, and 6 % when only considering market leaders. These learning rates are similar to those reported in other scientific studies. Thus, it can be concluded that the price of battery packs continues to decline and that costs reported by market leaders are lower than estimations in scientific articles.

Large cost reductions have been achieved in the recent years, partly as a result of economies of scale. The production volumes have increased, and the size of factories have increased, which enables a lower per unit production cost. However, Ciez and Whitacre [46] state that the potential from economies of scale is largely achieved with a production unit capable of producing 1 GWh of battery capacity annually. Still, the famous Tesla Gigafactory is planned to produce 35 GWh of batteries annually and is expected to result in significant cost reductions according to the manufacturer [64]. Cost reductions in the whole production process, including the supply chain should be considered when evaluating possible cost reductions from economies of scale, and these cost reductions can be relevant even as the production capacity has exceeded 1 GWh per year [68].

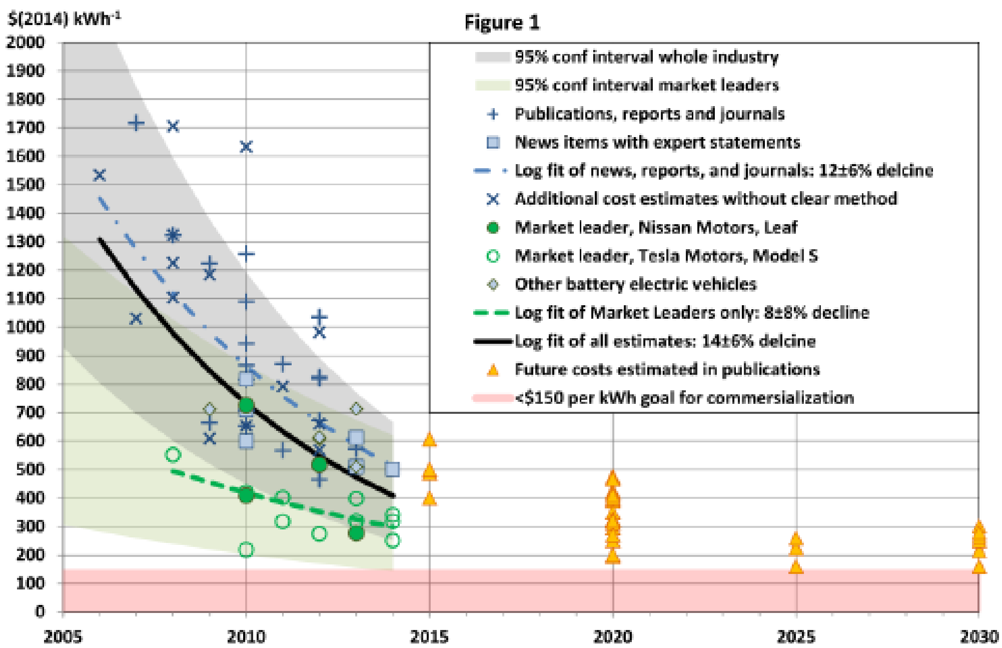

Figure 12 Cost of Li-ion battery packs in BEV, based on a variety of sources. [30].

Expanding the cost estimation comparison made by Nykvist and Nilsson [30] to the last years, it is evident that the cost estimates have decreased even further. In 2016 Tesla claimed to have achieved a battery pack cost of $ 190/kWh [69] and GM said that they were purchasing battery packs from LG Chem at a price of $ 215 /kWh [70]. In the same yearn Mc Kinsey [71] reported battery pack prices to have decreased to $227/kWh. They also stated that EVs could reach cost parity to conventional vehicles with battery prices below \$ 100/kWh. Bloomberg New Energy Finance reported a battery pack cost of \$273/kWh in 2016, a dramatically decreased price of \$ 162/kWh in 2017 and a updated future cost estimate of \$74/kWh for 2030 [72]. Recently, GM has stated that they are purchasing battery packs from LG Chem at a price of \$145/kWh, while Audi claimed to reach a battery cell cost of \$114/kWh [73]. The high price on batteries is often considered to be the major factor that make electrical vehicles relatively expensive compared to conventional vehicles. Even though it is challenging to quantify the actual costs of current batteries being produced, the battery costs are clearly trending downwards, which could result in a diminishing price difference between electric vehicles and conventional ICE vehicles. This analysis supports an increasing adoption of electric vehicles, and a method for adoption scenario creation is presented in the next chapter.

5 Vehicle fleet and powertrain scenarios as input to the model

A high degree of uncertainty surrounds the future of powertrains in the vehicle fleet. Current trends like emission reductions, electrification and an increased share of automation are reshaping the conditions for different powertrains. Technological development is also constantly enabling the vehicle manufacturers to produce improved propulsion system. The purpose of this study is not to forecast the adoption of different powertrains in the vehicle fleets, but to describe consequences with a certain development scenario, specifically related to GHG emissions and fuel demand. An electric and a conservative scenario were created for the market share of different powertrains in each of the three countries. The electric scenario describes the diffusion of electric vehicles, including PHEV and HEV, with the help of a Bass diffusion methodology [9]. The Conservative scenario is a less aggressive continuation of the current trend for powertrain shares in the national vehicle markets.

5.1 The current vehicle fleet in Finland, Sweden and Norway

Before constructing the powertrain scenarios, the vehicle fleet must be divided into different segments. For the purpose of the modeling work, light-duty vehicles are divided into passenger cars (PC) and light commercial vehicles (LCV). The passenger cars are further divided into five different segments based on their weights. Shares of vehicles in Norway by each weight segment and with a certain powertrain, can be seen in Figure 13. Shares of powertrains in the passenger car vehicle fleet in Finland, Sweden and Norway, as well as the share of registrations in 2016, are presented in Table 5 [32], [74], [75]. The weight segmentation is based on mass in running order, as defined in the European Commission regulation EU 1230/2012.

Table 5 Powertrain shares of the passenger car vehicle fleet and new vehicle registrations in Finland Sweden and Norway in 2016. A column with the name "fleet" refers to the vehicle fleet in 2016, and "New" refers to new vehicle registrations in 2016.

	FIN Fleet	FIN New	SWE Fleet	SWE New	NOR Fleet	NOR New
Gasoline	72.0 %	61.2 %	60.6 %	39.7 %	45.4 %	28.9 %
Diesel	26.9 %	32.7 %	32.1 %	51.7 %	47.5 %	30.5 %
BEV	0.0 %	0.2 %	0.2 %	0.8 %	3.7 %	16.0 %
Gasoline PHEV	0.1 %	1.2 %	0.3 %	2.4 %	1.2 %	12.7 %
Diesel PHEV	0.0 %	0.1 %	0.1 %	0.4 %	0.1 %	0.7 %
Gasoline HEV	0.7 %	4.4 %	1.1 %	3.7 %	2.1 %	11.1 %
Diesel HEV	0.0 %	0.1 %	0.0 %	0.0 %	0.0 %	0.0 %
Flexi-fuel	0.1 %	0.0 %	4.7 %	0.2 %	0.0 %	0.0 %
CNG	0.1 %	0.1 %	0.9 %	1.1 %	0.0 %	0.0 %
LNG	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
Fuel cell	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
ED95	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
Other	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %

The mass in running order includes the vehicle, with its fuel tank filled to at least 90 % of its capacity, the driver and standard equipment in accordance with the manufacturer's specifications. In this study, a passenger car is a vehicle used for the carriage of no more than eight passengers in addition to the driver, as in EC 2001/116. Vehicles used for the carriage of more than eight passengers are called buses. Buses are segmented into city-buses, coaches and minibuses. Heavy-duty vehicles are divided into the segments truck with trailer, tractor unit with semi-trailer and other. Each of these segments are subsequently divided into four weight segments, as described in Giacosa [7]. This adds up to 21 vehicle sub-segments, for which vehicles are further divided between 13 different powertrains. In total, the vehicle fleet model is based on 273 vehicle strata, and the same segmentation is implemented throughout the whole model.

The weight segmentation of passenger cars is necessary, because heavier vehicles consume more energy and some powertrains might be more suitable for vehicles with a certain weight. With the detailed weigh segmentation, there can be various scenarios for lighter and heavier vehicles. Figure 13 presents the Norwegian new registrations of passenger cars in 2016, by weight segment and powertrain. Worth noting is that diesel vehicles and PHEVs are clearly heavier than vehicles with other powertrains. The small vehicles are again clearly dominated by the gasoline powertrain.

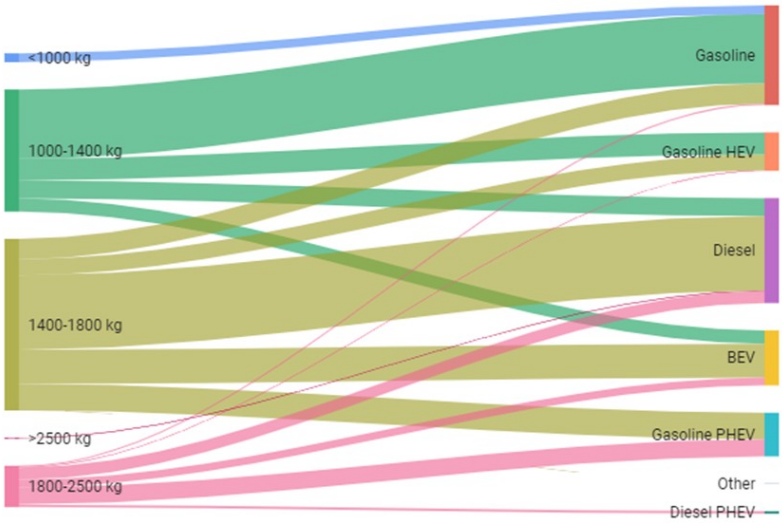

Figure 13 Diagram of Norwegian passenger car new registrations in 2016 by weight segment and powertrain segment. The height of each bar is proportional to its share of the total market [75].

The average weight of vehicles in a segment is taken from the vehicle fleet data and subsequently used in the energy consumption calculations. The average number of passenger is estimated based on a rough analysis, and the additional weight of the passengers and luggage are included in the vehicle weight. The average passenger weight is considered to be 75 kg and the luggage weight to be 20 kg. Weight assumptions used for the future in the Finnish model are presented Table 6. In each of the countries, the average weight of light-duty vehicles is assumed to remain unchanged until 2050 For other segments than passenger cars, an average load is also added to each vehicle segment, to account for the actual weight of the vehicle when it is driving. The load assumptions are explained in detail in Giacosa [7].

Table 6 Passenger car weight assumption for 2016-2050 in the Finland model.

PC sub-segment	Mass in running order [kg]	Average number of passenger	Total mass [kg]
PC 0-1000 kg	938	1.2	957
PC 1000-1400 kg	1246	1.2	1265
PC 1400-1800 kg	1555	1.4	1593
PC 1800-2500 kg	1949	1.6	2006
PC 2500 kg+	2916	2.0	3011

5.2 The electric and conservative powertrain scenarios used in the model

The powertrain scenarios are made separately for all five weight segments of passenger cars and light commercial vehicles. A two-step process is utilized for passenger cars, where the first step is a weight segment split and the second step a powertrain split. The passenger car weight segment split for 2016-2030 is shown in Figure 14. The weight segment split scenario is based on an ad-hoc diffusion method, where it is assumed that the heavier segments will make up a larger share of the new vehicles in Finland and Norway. Increasing vehicle weights have been the trend lately, and this trend is then continued. Electric vehicles are also considered to be heavier due to the low gravimetric energy density of the battery, which means that a large adoption of electric vehicles can cause the vehicles to be heavier. Several factors are also suggesting lower vehicle weights, such as lightweighting measures, engine downsizing and lower emissions, lower price and better urban accessibility for smaller and lighter vehicles. It is assumed that the Swedish weight split stays unchanged, as the vehicles are already relatively heavy.

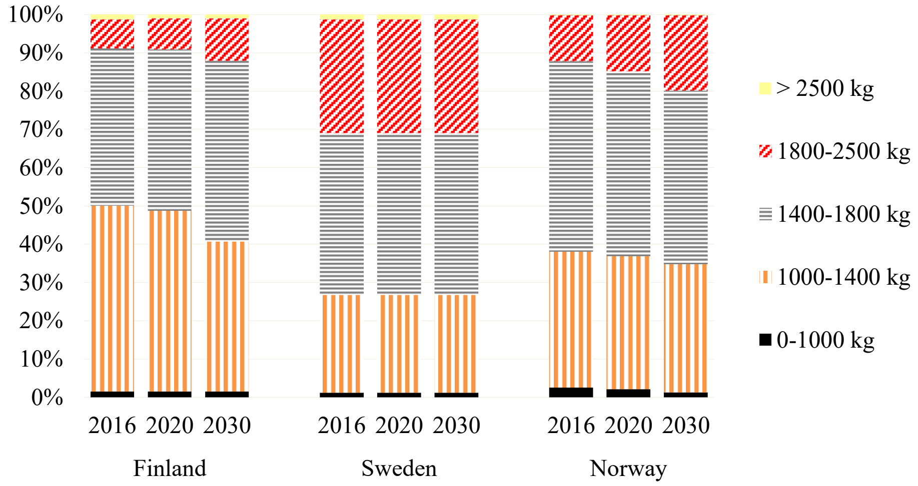

Figure 14 Passenger car weight segment split for new vehicles in Finland Sweden and Norway 2016-2030.

The electric and conservative powertrain split scenarios, determine the share of each of the 13 powertrains for new vehicle registration in each of the five specific weight segments and also for light commercial vehicles. As an example of the two-step new vehicle registration process, the electric scenario total passenger car sales in 2020 is 120 834, of which 50 967 are in the 1400-1800 kg, which represents 42.2 %. In that weight segment, the share of gasoline PHEVs is 9.3 %, which means that 4716 new gasoline PHEVs in the weight range 1400-1800 kg are introduced in the Finnish vehicle fleet in 2020 in the electric scenario. The combined electric scenario powertrain splits for new passenger cars in all weight segments in Finland, Sweden and Norway are presented in Figure 15.

In the Finnish conservative scenario, the number of BEVs, PHEVs and FCVs in 2030 is 250 300 in total, which is in accordance with the Finnish Energy and Climate strategy for 2030. The Finnish Energy and Climate strategy for 2030 sets a target on over 250 000 BEVs, PHEVs and FCVs in total in the Finnish vehicle fleet in 2030 [3]. Of the vehicles in the scenario, roughly 248 000 are passenger cars, 1700 LCVs, 30 HDVs and 400 Buses. Of these passenger cars, there are 140 000 BEVs, 110 000 PHEVs and only two FCVs. A target in the strategy is also set on 50 000 vehicles running on gas, that is CNG and LNG, which is also achieved in the Finnish conservative scenario, as the number of CNGs and LNGs is 56 800. It is worth noticing that the weight and powertrain scenarios are not originally made for number of vehicles, but for vehicle shares. The actual number of new vehicles is a model result based on powertrain share and new vehicle sales. The new vehicle sales is based on assumptions on transport need, average vehicle mileage, vehicles leaving the fleet and the weight and powertrain scenarios. The methodology for new vehicle sales is explained in Kilpeläinen [6]. Example results of the powertrain scenarios in the Matero model are presented in chapter 7.

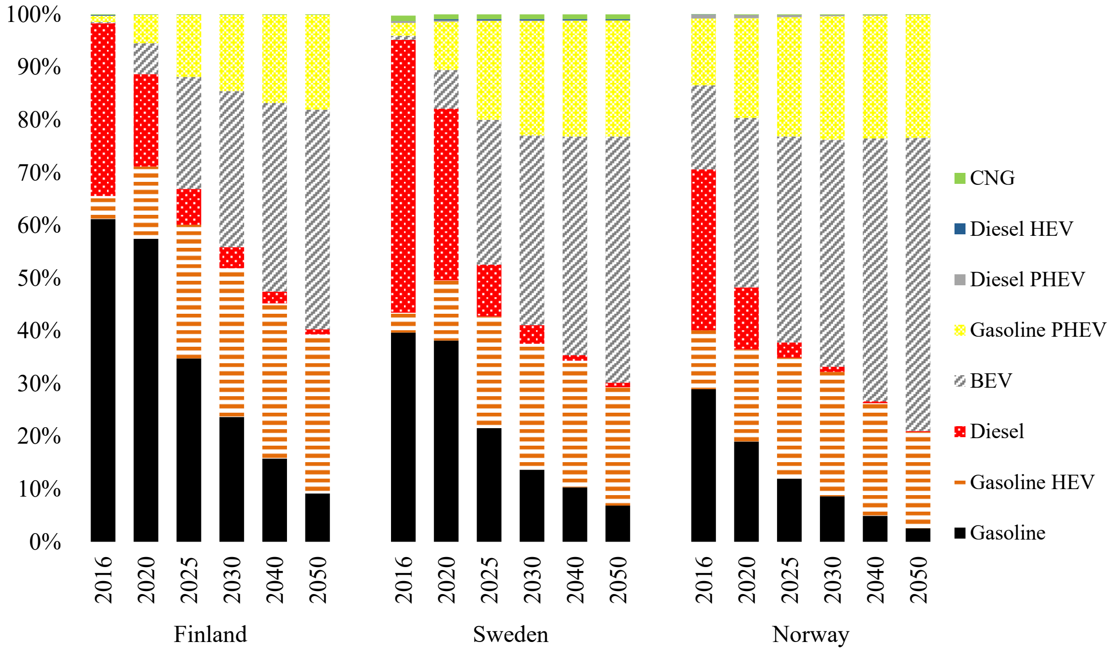

Figure 15 Electric scenario passenger car powertrain shares for new vehicles in Finland, Sweden and Norway year 2016-2050.

5.3 Development of reported CO_2 emissions in the powertrain scenarios

As an attempt to reduce CO_2 emission from road transport, the European Parliament and Council have set CO_2 emission targets for new vehicles sold by vehicle manufacturers. Passenger car CO_2 emissions are regulated in EC 443/2009 and light commercial vehicles in EU 510/2011. The CO_2 target is on the weighted average CO_2 emissions of vehicles registered in EU by a vehicle manufacturer, or a group of manufacturers. Manufacturers who fail to achieve the target levels, are subject to a fine based on the deviation from the target and the number of vehicles registered. The regulation is enforced on all large vehicle manufacturers, and manufacturers that contribute with less than 300 000 registrations a year can be subject to derogations from the targets. The targets are gradually tightening until 2021 for passenger cars when the target is 95 gCO_2/km, and until 2020 for light commercial vehicles when the target is 147 gCO_2/km. [76]. The emissions are measured for vehicle types in the New European driving cycle (NEDC), which is a standardized test cycle used for type-approval of passenger cars and light commercial vehicles in the EU. Norway is not part of the EU, but the Norwegian government has set an 85 gCO_2/km target for vehicles registered in Norway in 2021 [5].

The CO_2 target in gCO_2/km for passenger cars is set as

$$\varphi_{PC} = 95 + a \cdot (M - M_0) \tag{2}$$

where a is 0.0333, M the average mass of manufacturers registered vehicles and M_0 the reference mass which was set to 1392.35 kg as from 2016. For light commercial vehicles the target is set as

$$\varphi_{LCV} = 147 + b \cdot (M - M_0) \tag{3}$$

where a is 0.096, M the average mass of manufacturers registered vehicles and M_0 the reference mass will be 1766.35 kg as from 2018. The reference mass M_0 is adjusted every three years, to reflect the average mass of registered vehicles in EU. As the reference mass changes, the targets will also slightly change. Certain super-credits have been given to vehicles with for example emissions lower than 50 gCO_2/km and some eco-innovations that cannot be seen in the test. These super-credits are phased-out prior to 2020 and are not accounted for in this study. [76]. The targets are set on EU wide registrations, and cannot be directly translated into a target for a specific country. However, the average vehicle weights vary between countries, and it is reasonable to think that countries with a higher average weight, will have higher specific emissions. Taking into account a countries average vehicle weight, e.g. 1620 kg for passenger cars in Sweden 2016 when the reference mass is 1392 kg, an indicative target can be calculated for that country using equations 2 for passenger cars and 3 for light commercial vehicles. In 2016 the average passenger car weight in Finland was 1440 kg, which makes the indicative target 96.6 gCO_2/km. Similarly, for passenger cars in Sweden, the average weight was 1620 kg, making the indicative target 102.6 gCO_2/km.

To meet the targets, vehicle manufacturers can improve the efficiency of vehicles or sell vehicles with powertrains that have lower emissions. The annual efficiency improvements for PC and LCV are covered in Giacosa [7], and are set to be 1.4 % between 2016 and 2021 for all powertrains. After this, the annual efficiency improvement is 1.0 % in 2022 and decreasing year by year with a factor of 0.95 until 2050. Apart from improving the efficiency of conventional vehicles, vehicle manufacturers can sell vehicles with low CO_2 emissions, such as electric vehicles, to improve their average CO_2 emissions of sold vehicles. Reported CO_2 emissions in gCO_2/km as a function of mass in running order for vehicles registered in Sweden in 2016 is presented in Figure 16.

For the purpose of this study, the reported CO_2 emissions as a function of mass in running order, is called an emission slope. The emission slopes are derived from vehicle fleet data delivered by SCB, and are obtained using linear regression. The methodology is further elaborated in section 6.1. Having the CO_2 emissions as a function of mass is necessary, as heavier vehicles tend to have higher specific emissions. For customers choice of vehicles, the type and size of the vehicles are generally more important than the CO_2 emissions [22]. As type and size, typically is proportional to the mass, it is more likely that customers change to powertrains with lower emissions, compared to a change to smaller vehicles. However, with lightweighting and downsizing measures it is also possible to achieve a lower mass without affecting the type and size of the vehicles. Furthermore, large batteries increase the mass of a vehicle, without increasing the size of a vehicle. Regardless of the vehicle mass, vehicle manufacturers will likely have to sell a significant share of electric vehicles to meet with the CO_2 targets.

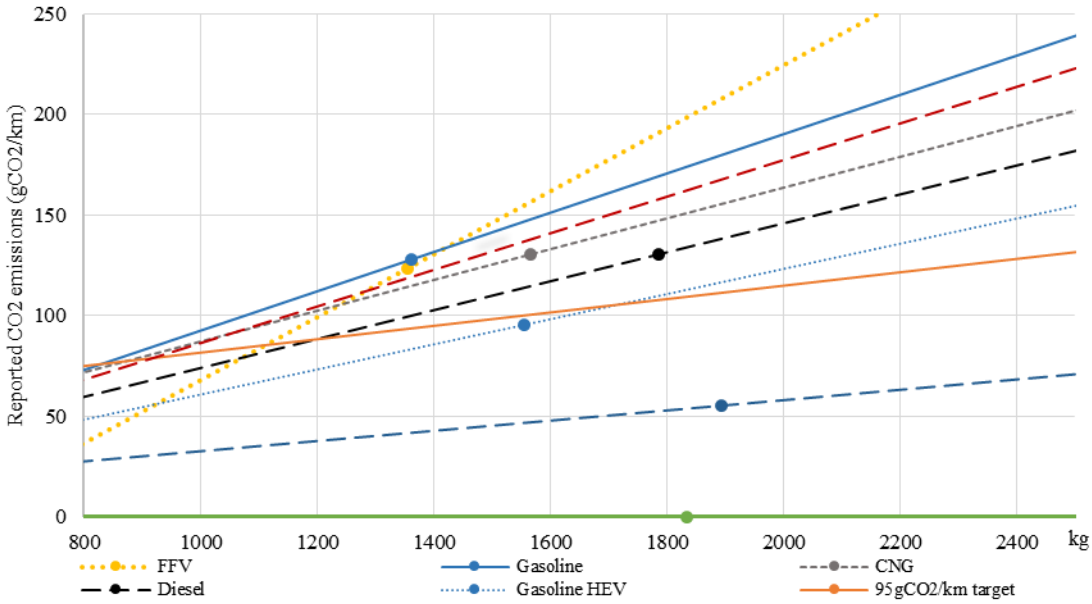

Figure 16 Reported CO_2 emissions by powertrains as a function of mass in running order for vehicles registered in Sweden in 2016. The average weight of the vehicles with a certain powertrain is marked by a dot.

Only the powertrains with statistically relevant data are shown in Figure 16. In the SCB data on vehicles registered in 2016, there were 193 550 diesel vehicles, 149 291 gasoline, 13 485 Gasoline HEVs, 3840 CNG, 2994 BEVs and 771 FFVs with values for mass in running order and CO_2 emissions. The gasoline and FFV powertrains have high CO_2 emissions, followed by CNG, Diesel and Gasoline HEV. The SCB data did not include relevant information on CO_2 emissions for PHEV, which is why the Gasoline PHEV energy consumption slope used in the Matero model is plotted in the graph. The slope for PHEVs reflects a 55 % driving share in electric mode and 45 % with the ICE, multiplied by a factor of 1.05. As seen, PHEVs have significantly lower emissions and BEVs have no TTW CO_2 emissions. The FFV energy consumption slope is significantly steeper than the other slopes, which is a result of the vehicles that happened to be registered, and not necessarily a characteristic of the powertrain. There were only 21 unique CO_2 values for FFVs, which refers to 21 unique vehicle models, and therefore some specific vehicle models can have a large impact on the emission slope.

The 95 gCO_2/km target, as defined in equation 2, is also plotted in the figure, as well as the average mass of vehicles with a certain powertrain indicate by a dot. The red dashed line represents the emission slope for the gasoline powertrain in 2021, assuming a 1,4 % annual efficiency improvement between 2017 and 2021. Any kind of sustainability of fuels is not taken into account in the reported CO_2 emissions, but reference fuel emission factors in Table 8 are used. This gives a serious disadvantage to for example FFV vehicles, as approximately 80 % of the E85 fuel typically is renewable. Figure 16 can also give some insight into what vehicle manufacturers can do to decrease their average CO_2 emissions of vehicle registrations. As the 95 gCO_2/km line represents the target, any vehicle above it will contribute to a too high emission value, whereas any vehicle below the line will contribute to a lower emission value. The vertical deviation from the 95 gCO_2/km line, tells how much a vehicle contributes to a higher or lower emission value. Whether these reported CO_2 emission values then represent the real-world emissions or not is discussed in the following chapter.

In 2016 the average CO_2 emission of passenger cars was 125 gCO_2/km. With an average weight of 1640 kg, the weight corrected target would be 103 gCO_2/km, leaving the Swedish new registrations 22 gCO_2/km above the target. Assuming the 1,4 % annual efficiency improvement between 2017-2021, the compounded efficiency improvement is 6,8 %. Reducing the 2016 emission value 125 gCO_2/km by 6,8 % leaves an average emission value of 116,5 gCO_2/km. Thus, the reduction from efficiency improvements is 8,5 gCO_2/km. To achieve the 103 gCO_2/km level, the average fleet emissions should be reduced by 13,5 gCO_2/km as a result of a shift to more efficient powertrains. Of the registrations in Sweden, 97,5 % had a mass in running order heavier than 1100 kg. Studying the emission slopes in Figure 16, hybridization and electrification appears as the only options for vehicle manufacturers to comply with the target. Furthermore, the relatively high average weight of BEVs and PHEVs, will also contribute to a higher CO_2 emission target, as defined in equation 2 and 8. The higher CO_2 emissions of gasoline compared to diesel is also worth noticing. A shift away from diesel powertrain to gasoline, will add to higher average CO_2 emissions, and further spur the need for hybridization and electrification. As a result, vehicle manufacturers can be expected to remain reluctant to a shift away from passenger cars with diesel powertrain, due to the higher CO_2 emissions.

Development of average reported CO_2 emission values in the Matero model electric scenario is presented in Figure 17 for passenger cars and light commercial vehicles in Finland, Sweden and Norway. Blue lines refer to Finland, yellow lines to Sweden and red lines to Norway. An additional dashed blue line (FIN PC No efficiency) refers to the average CO_2 emissions of Finnish passenger car registrations, assuming that the powertrain efficiencies do not improve. This way, the difference between the line FIN PC and FIN PC No efficiency is the emission reduction attributed to efficiency improvement, and the rest of the improvement is a result of a shift to more efficient powertrains. In 2016 the average CO_2 emissions of the Finnish new PC registrations was 121 gCO_2/km. In the electric scenario, a level of 65 gCO_2/km is achieved in 2030. Of this reduction, 11 gCO_2/km is attributed to efficiency improvements and 44 gCO_2/km to a shift to more efficient powertrains.

The reported CO_2 emissions are used as a base for the fuel consumption of light-duty vehicles in the Matero model. Several studies have shown that the NEDC test method does not reflect emissions in real-world driving conditions, and that the real emissions can be as much as 40 % higher [77]. Thus, a reduction in CO_2 emissions measured with the NEDC driving cycle is a combination of actual efficiency improvements and vehicle manufacturers ability to optimize the vehicle to show low emissions in the test. The real-world emissions are assessed in the next chapter. The NEDC test method will be replaced by the Worldwide Harmonized Light Vehicles Test Procedure (WLTP). Still, the reduction targets set in EC 443/2009 and EU 510/2011 are based on the NEDC test method, which is why the WLTP test method is not considered in this study.

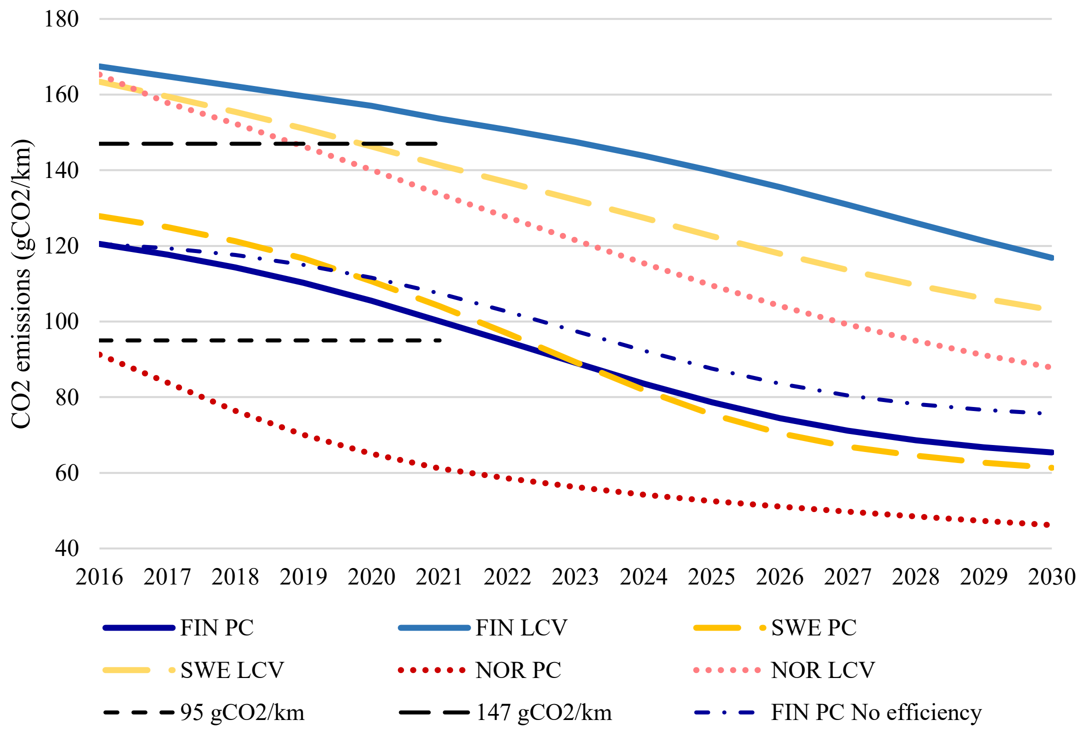

Figure 17 Electric scenario reported CO_2 emissions for PC and LCV in Finland, Sweden and Norway 2016 – 2030.

5.4 Methodology for the creation of powertrain scenarios

In the electric scenario, the market shares of the powertrains BEV and PHEV are modeled using Bass diffusion of innovations [9]. The Bass model generates unconditional predictions based on historical values, as it is a function of time with one variable. The model creates market outcomes utilizing the historical values and a fixed market potential, or saturation level. That is, the model can be used to estimate the speed of diffusion of an innovation, however, it cannot estimate the total market penetration of an innovation, in this case a certain powertrain.

The model considers social interaction between consumers to describe the adoption of new innovations. Consumers are divided into innovators and imitators. Innovators are thought to be impacted by a mass-media effect, and imitators by a word-of-mouth effect. In the model, these groups are represented respectively by a coefficient of innovation p and a coefficient of imitation q. Initial adoption to the product or technology is made by both innovators and imitators. The timing of adoption for innovators is not affected by other people who have already adopted, whereas imitators are influenced by previous adopters. [9]. Figure 18 illustrates the impact from innovators and imitators on the total adoption rate.

The Bass model has previously been used for modelling the adoption rate of new powertrains in other studies [78]. It has also further been modified to include e.g. price information, as in the generalized bass model [79]. In many applications, certain customer preferences and choice sets have also been included [80]. No such modifications or additions are utilized in this study, as the adoption rate is based on historical sales figures, and the historical data does not include information regarding pricing or customer behavior.

In the Bass model, the market share of an innovation at time t is described by equation 4.

$$\frac{f(t)}{1-F(t)} = p + q \cdot F(t) \tag{4}$$

where $F(t)$ is the cumulative adoption at time t, $f(t) = \frac{\partial F(t)}{\partial t}$ the density of adoption at time t, p is the coefficient of innovation and q is the coefficient of imitation. If the market potential is not the whole market, the parameter M for market potential is added to the equation. The market potential describes the saturation level for the adoption curve, and when M is known, the Bass equation takes the form

$$\frac{f(t)}{M-F(t)} = p + \frac{q \cdot F(t)}{M}. \tag{5}$$

The market adoption at time is then,

$$f(t) = M \cdot p + (q-p) \cdot F(t) - \frac{q}{M} \cdot F(t)^2. \tag{6}$$

In this study market shares of different powertrains are modeled, thus $F(t)$ is the market share of a specific powertrain, $f(t)$ the adoption rate of that powertrain and M the market potential of that powertrain.

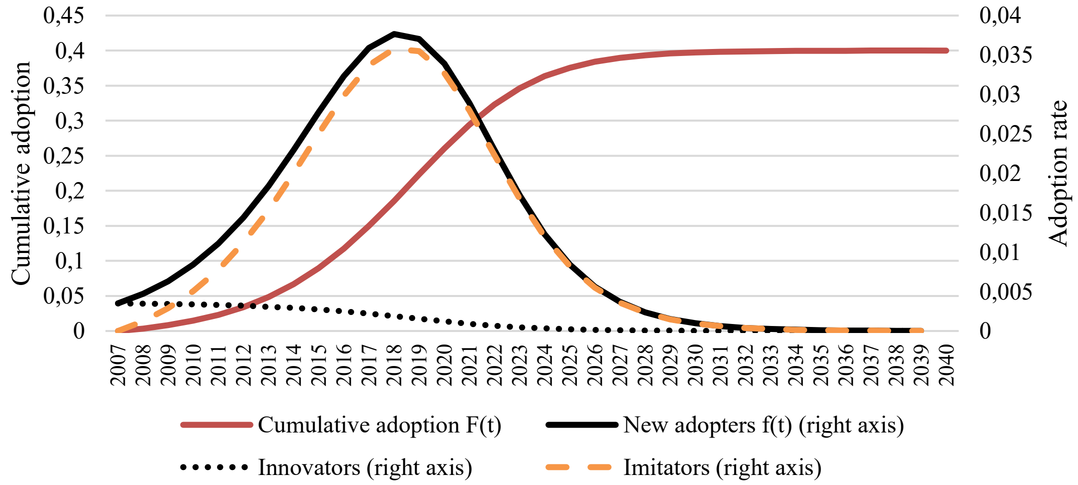

Figure 18 Bass diffusion model for BEV in the segment PC 1000-1400 kg in Norway with a fixed market potential of $M = 0{,}4$. The dotted lines represent the adoption rate for new adopters; innovators ($p = 0{,}0087$) and imitators ($q = 0{,}3597$).

When historical figures on market adoption of an innovation are available, the historical sales figures can be fitted to the Bass model. Bass [9] originally suggests an ordinary least squares (OLS) method for the adoption of historical sales figures into the model. Various other methods could also be used for the fitting of empirical data to the model, e.g. maximum likelihood estimation, nonlinear least square method and algebraic estimation methods [81]. For the purpose of this study a generalized reduced algorithm, the GRG nonlinear solving method [82] is used to fit the Bass model to a set of empirical data $H = \{(t_i, H(t_i)|i = 1,2, \dots, K\}$. $G(p,q)$ in equation 7 is the squared difference between the model cumulative adoption $F(t)$ and the historical cumulative adoption $H(t)$. The GRG nonlinear method is available in the MS Excel solver add-in, and used for minimizing

$G(p,q)$ as in equation 5. When the potential market share M is predetermined, the minimization is performed by changing the coefficients p and q.

$$G(p,q) = \sum_{i=0}^{K}\left(F(t_i) - H(t_i)\right)^2 \tag{7}$$

$$\min_{t_i \in K} G(p,q) = \min_{t_i \in K} \sum_{i=0}^{K}\left(F(t_i) - H(t_i)\right)^2 \tag{8}$$

Norway is the global leader in adoption of BEV and PHEV, and the Norwegian historical vehicle registration data [75] is used to create adoption curves for electric vehicles. Figure 19 presents results of the diffusion model, when using registration data for battery electric vehicles in the vehicle segment PC 1400-1800 kg and a fixed market potential value $M = 0{,}4$. Historical data is used from year 2007-2016, as electrical powertrains started to adopt a share of the market in Norway around 2007.

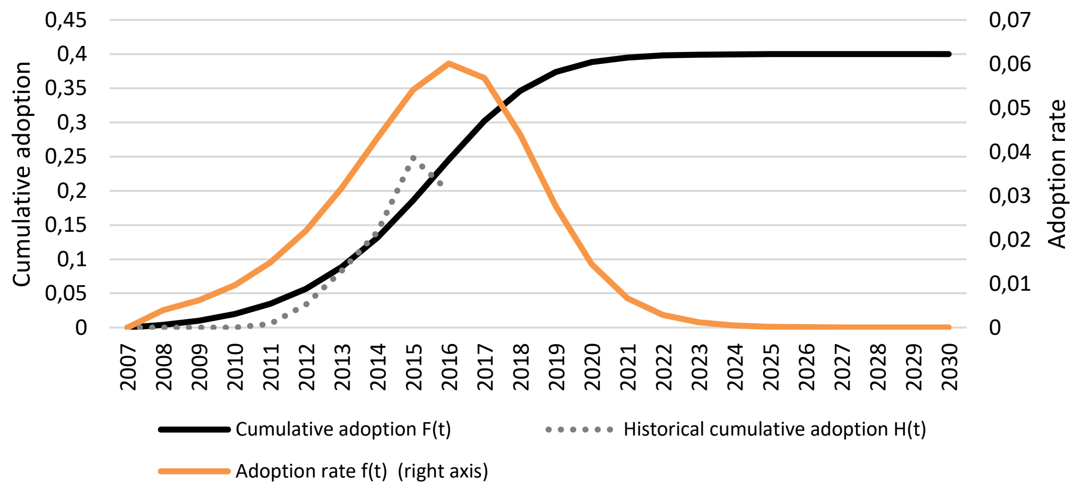

Figure 19 Bass diffusion model adapted to BEV market share in the segment PC 1400-1800 kg in Norway. A fixed market potential is set at $M = 0{,}4$. Historical values are based on data on new vehicle registrations [75].

Utilizing the Bass diffusion model for forecasting innovation diffusion, the estimation of the potential market penetration M is critical, as it is the saturation limit for the diffusion curve. In this study, the focus is on scenario creation and therefore various values for the market penetration are used. As seen in Figure 19, the diffusion of battery electric vehicles as estimated by the Bass model is quite rapid. Adapting the diffusion model to the historical data, for the segment PC 1400-1800 kg in Norway, with the GRG nonlinear method (5), gives a value of 0,0099 for the coefficient of innovation p, and 0,5825 for the coefficient of imitation q. Historical values for p and q for different innovations are compared in Table 7. A meta-analysis by Sultan et.al. [83] found an average for p to be 0,03 and for q to be 0,38 when they compared 213 applications. As there is no clear convergence between the coefficients p and q in the different applications, it is motivated to use the sales history for each specific BEV weight segment to estimate the coefficients. In the scenario creation, the Bass diffusion is mainly used for the adoption of BEV and PHEV, as well as inverted in a few cases for the decrease in the market share of diesel powertrain. In the case that relevant historical data is not available for a specific segment, the adoption rate of the total powertrain segment is used. Thus, the values of p and q obtained for the whole powertrain segment, is used for each weight segment. In general, it is noticed that the share of innovators is quite low, which also can be seen in Figure 18.

Table 7 Coefficients of innovation (p) and imitation (q) for different applications, used in the Bass diffusion model.

Innovation	p	q	Source
BEV PC 1400-1800 kg	0.0099	0.5825	
BEV PC 1000-1400 kg	0.0088	0.3577	
AFV in Brasil	0.0000585	0.2422	Benvenutti et al. [84]
HEV in USA	0.0026	0.709	McManus and Senter [85]
Toyota Prius in Japan	0.0016	1.4551	Massiani and Gohs [86]
Civic Hybrid in Japan	0.0034	0.6313	Massiani and Gohs [86]
Ford Escape in Japan	0.0367	0.4322	Massiani and Gohs [86]
Average of 213 applications	0.03	0.38	Bottomley [87]

6 A quantitative model for vehicle fleet and GHG emission development

A quantitative model was created for the estimation of GHG emissions and energy demand from road transport in Finland, Sweden and Norway. Here the model is referred to as the Matero model, or simply the model. When referring to the model specifically for one of the countries, the terms the Finnish model, the Swedish model and the Norwegian model are also used. In this study, road transport is defined as the use of passenger cars, light commercial vehicles, heavy-duty vehicles and buses. A stock-flow-cohort methodology was used to model the vehicle fleet in the future. The vehicle fleet model is presented in Figure 20. The vehicle fleet in a certain year is modeled through a stock of vehicles moving on from the fleet in the previous year and new vehicle vehicles. Number of new vehicles is derived from transport need scenarios, so that the new vehicle fleet covers the total driven mileage in the transport need scenario. The size and powertrain of the new vehicles is determined by the powertrain scenarios which are described in chapter 4. A more detailed description of the vehicle fleet model is described in Kilpeläinen [6]. In the model, the vehicle fleet is divided into 21 sub-segments and 13 powertrains. Let i denote the powertrain ($i = 1,2,\dots,13$), j the model year ($j = 1,2,\dots,31$) and k the sub-segment ($k = 1,2,\dots,21$). Then, the vehicle fleet at year t can be described as

$$A^t = \sum_{i=1}^{13} \sum_{j=1}^{31} \sum_{k=1}^{21} A_{i,j,k}^t. \qquad (9)$$

This way the vehicle fleets in 2017-2050 can be modelled using certain input values and scenarios. In Figure 20, the gray boxes are representing some of the inputs that are needed. Powertrain scenarios and vehicle fleets have been described in chapter 5 and the transport need is presented in section 7.2. The net-flow intensity rates determine the share of vehicles remaining in the fleet going from year t to year t+1. These rates are derived from how vehicles in a certain sub-segment have been leaving the fleet between 2012 and 2016. A more detailed description of the net-flow intensity rates can be found in Kilpeläinen [6]. When the vehicle fleet is known for each year, the energy demand can be calculated, which is presented in the next section.

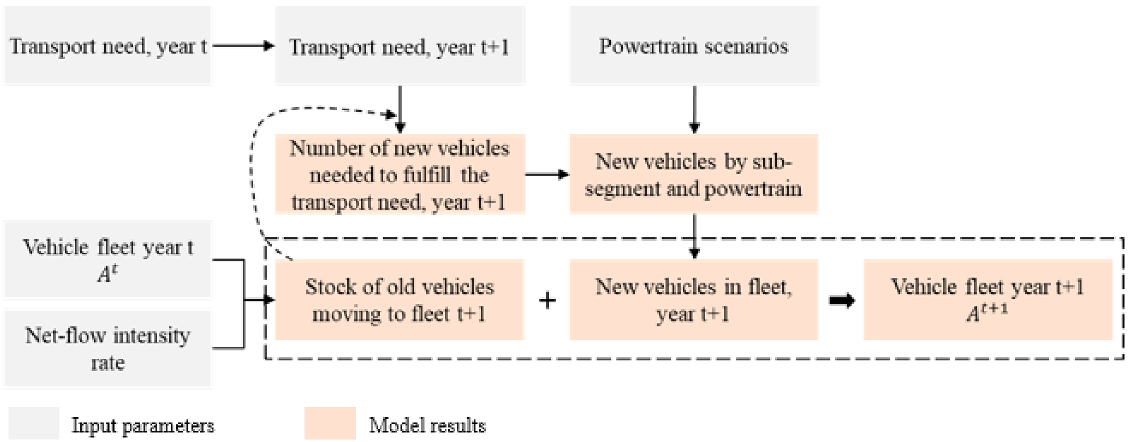

Figure 20 Schematic diagram for the vehicle fleet model. The vehicle fleets in 2017-2050 are based on the stock of vehicles remaining in the fleet from the previous year and new registrations. Net-flow intensity trates are used to derive the stock of vehicles remaining in the fleet from the previous year and the new registrations are added so that the vehicle fleet covers the total driven mileage in the transport need assumptions.

6.1 Fuel economy and energy consumption calculations

The emissions can be estimated both from fuel sales and from vehicle mileage. The model uses fuels sold to the road transport sector to estimate emissions for 2012-2016, and vehicle mileage and the vehicle fleet to estimate energy demand, fuel consumption and emissions for 2017-2050. The general calculation methodology is described in Figure 21. The used emission factors and energy factors are found in Appendix 1.

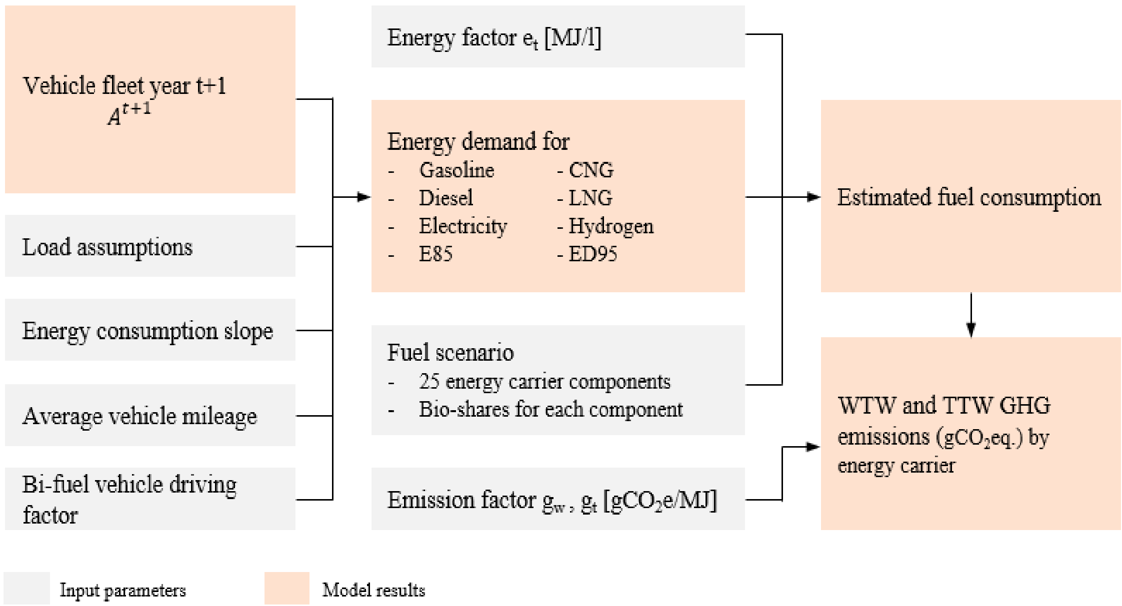

Figure 21 Schematic structure of the model energy and emission calculations.

The considered GHG emissions are both well-to-wheel (WTW) and tank-to-wheel (TTW) emissions. The methodology for estimating energy consumption and GHG emissions from the road transport sector is consistent with the European standard EN 16258 as well as the IPCC Guidelines for National Greenhouse Gas Inventories [10]. The greenhouse gases considered are limited to CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). These are also the GHG gases listed in Annex A of the Kyoto Protocol [12].

The energy consumption of passenger cars and light commercial vehicles is obtained from the type-approval reported CO_2 emission values, as measured in accordance with Annex XII to Regulation EC 692/2008 and Regulation EC 715/2007 [88], [89]. The test method utilizes the New European driving cycle (NEDC) and is a standardized test method used for type-approval of light-duty vehicles in Europe. The test-cycle consists of an Urban driving cycle and an Extra-urban driving cycle to simulate normal driving conditions. The CO_2 emission value of a specific vehicle is reported in gCO_2/km. The fuels used in the test are the reference fuels stated in Regulation EC 692/2008 [88]. To convert fuel economy to energy consumption, TTW emission factors for the reference fuels are used, which are presented in Table 8. These are calculated using CO_2 emission factors for the fuel components as in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [10].

Table 8 TTW emission factors for the reference fuels used in the NEDC type-approval test.

Reference fuels	TTW emission factor [gCO_2/MJ]
Gasoline (E5)	69.36
Diesel B5	74.20
E85	70.48
Gas (methane)	56.10

For a specific powertrain, the energy consumption of a vehicle can be described as a linear function of the vehicle's mass in running order. For the purpose of this study, the linear function is called an energy consumption slope, denoted $e_{i,j}$, where i represents the powertrain and j the take into use year. The energy consumption slopes are calculated with simple linear regression for each powertrain and year model, using the specific energy consumption obtained from NEDC test results on CO_2 emissions. Values for the specific energy consumption of each vehicle, is retrieved from the vehicle fleet data [32], [74], [75].

To calculate the energy consumption, let $m_{i,j,k}$ be the mass of a vehicle with powertrain i, take into use year j and sub-segment k, then the type-approval energy consumption ($\varphi_{i,j,\boldsymbol{k}}$) is calculated as in equation 10.

$$\varphi_{i,j,k} = e_{i,j} * m_{i,j,k} \tag{10}$$

The type-approval CO_2 emissions values have consistently been proven too low [77], as mentioned in section 5.3. A real-world driving factor (η_i) is needed to adjust for discrepancies between the type-approval test and real-world driving conditions. The real-world fuel consumption is calculated with equation 11.

$$\phi_{i,j,k} = \varphi_{i,j,k} * \eta_{i,j} \tag{11}$$

Letting $s_{i,j,\boldsymbol{k}}$ be the average mileage of vehicles with powertrain i, take into use year j and vehicle sub-segment k, the energy consumption in year n can be calculated as

$$\varepsilon^n = \sum_{i=1}^{13} \sum_{j=1}^{31} \sum_{k=1}^{5} \varphi_{i,j,k} * \eta_{i,j} * s_{i,j,k} * A_{i,j,k}^t \tag{12}$$

where $A_{i,j,\boldsymbol{k}}^t$ is denoting the vehicle fleet in the end of year n. The average vehicle mileage is explained in chapter 6.

The vehicle fleet does not contain a statistically relevant number of vehicles for every segment, powertrain and year model to obtain $e_{i,j}$. In that case, the energy consumption is derived using relative energy consumption to a similar vehicle segment. The relative energy factors are presented in Table 9. Energy consumption and emissions are calculated based on eight energy carriers. These are Gasoline, Diesel, Electricity, E85, CNG, LNG, Hydrogen and ED95. Gasoline is consumed by the powertrains Gasoline, Gasoline PHEV and Gasoline HEV. Diesel is consumed by the powertrains Diesel, Diesel PHEV and diesel HEV. PHEV, CNG and FFV are typically so called bi-fuel vehicles, that can utilize two different powertrains. Factors called bi-fuel vehicle driving factors are incorporated in the model, which determine the share of mileage covered by each powertrain for vehicles that can use two powertrains. The PHEVs are considered to drive 55 % of the mileage in electric mode [22], and CNG vehicles to drive 100 % on CNG. FFVs can use both E85 and gasoline. They are considered to drive 100 % on E85 in Finland, 15 % in Sweden and

100 % in Norway. The percentage is derived from the data on fuel consumption and vehicle mileage. Using these factors, energy consumption of the 13 powertrains are split into the eight energy carriers.

Table 9 Relative energy factors used in the model for different powertrains.

Powertrains	Factor (MJ/MJ)	Source
FCV % of BEV	250,0 %	[90]
Flexifuel % of gasoline	100,0 %	[90]
ED95 % of diesel	100,0 %	[90]
Electricity % of diesel	30,0 %	[90]
CNG % of diesel	115,0 %	[91]
LNG % of diesel	115,0 %	[91]
Gasoline % of diesel	115,0 %	[91]
Gasoline HEV % of gasoline	85,0 %	[90]
Diesel HEV % of diesel	85,0 %	[90]
Gasoline PHEV % of Gasoline / BEV	105,0 %	Assumed
Diesel PHEV % of Diesel / BEV	105,0 %	Assumed

The efficiency of powertrains is expected to increase in the future, which is accounted for through future vehicle efficiency scenarios as previously described. The scenarios were created for the yearly efficiency improvement of all powertrains. The efficiency improvement in a specific year can be described by $\delta_{i,j}$, where i refers to the powertrain and j to the take into use year. As the efficiency improvement during year j will be effective in the fleet the next year, the annual efficiency improvement factor from the previous year should be used when calculating the efficiency for a certain take into use year. As the efficiency is modeled as an energy consumption slope, energy consumption slopes for future vehicles are calculated as

$$e_{i,j} = e_{i,j-1} * \delta_{i,j-1} \tag{13}$$

For vehicles utilizing two powertrains, the energy is split between the two powertrains. The bi-fuel vehicle driving factors are used to calculate the share of energy from each powertrain. This methodology is elaborated in Kilpeläinen [6]. The energy consumption from the energy carriers is then used to calculate TTW and WTW GHG emissions. This is in accordance with the 2006 IPCC Guidelines for national Greenhouse Gas inventories, which states that emissions from road transport should be calculated from the consumption of fuels [10]. Each of the energy carriers can be a combination of different components. The model is constructed to take 29 different energy carrier components into account. These are presented in Appendix 1.

Let the energy consumption in year n for each energy carrier component be denoted f_d^n. Then the TTW GHG emissions (G_t^n) can be calculated as

$$G_t^n = \sum_{d=1}^{29} f_d^n * g_d \tag{14}$$

where d is representing the energy carrier components ($d = 1,2, \ldots ,29$) and g_d the TTW emission factor for the components. The WTW GHG emissions are calculated with equation 15 using the WTW emission factor h_d.

$$G_w^n = \sum_{d=1}^{29} f_d^n * h_d \tag{15}$$

In the TTW emission calculation, the emissions from biofuels, electricity and hydrogen are considered zero as in accordance with EN 16258. The biofuels are renewable and are therefore considered not to produce any anthropogenic CO_2 emissions. Electricity and hydrogen emissions are considered zero, as the local emissions are zero and CO_2 emissions mainly arise from production facilities that belong to the EU ETS-sector. Including those emissions in the national emission inventories would thus cause the emission to be accounted for both in the ETS-sector and in the road transport sector that belongs to the effort sharing sector. [19].

In the WTW GHG emission calculations the sustainability of biofuels and bioliquids should be accounted for in accordance with Article 19 of directive EC 2009/28 [92]. The WTW GHG emissions of biofuels vary significantly, depending e.g. on feedstock, production process and distribution. Directive 2009/30/EC sets sustainability criteria on biofuels, which quantify the minimum GHG savings from the use of biofuels compared to comparable fossil fuel. For 2017 biofuels should provide GHG savings of at least 50 %, and from 2018 the savings should be at least 60 %. In the model, the average WTW GHG savings from biofuels and bioliquids is considered to be 70 %. For simplicity, this factor is used to calculate the WTW GHG emission factor for all bioliquids substituting gasoline and diesel. Thus, the WTW GHG emission factor for bioliquids substituting gasoline, is considered 30 % of the emission factor of gasoline. Similarly, the emission factor of bioliquids substituting diesel, is 30 % of the diesel emission factor.

According to the 2006 IPCC Guidelines, non-combustive emissions from the use of urea-based additives in catalytic converters, should be included in the TTW emissions. These emissions mainly arise from the use of AdBlue in selective catalytic reduction (SCR) systems. SCR systems are used in diesel vehicles to reduce NO_x emissions. AdBlue is a registered trademark for an aqueous solution made of 32,5 % urea ($CO(NH_2)_2$) and 67,54 % deionized water. When the solution is injected to the exhaust gas, ammonia (NH_3) and isocyanic acid (HNCO) is formed through thermal decomposition, after which the isocyanic acid and water vapor form ammonia and carbon dioxide as in equation 16. NO_x is then reduced by NH_3 in the presence of a catalyst. [93].

$$CO(NH_2)_2 \rightarrow 2NH_3 + CO_2 \tag{16}$$

The CO_2 emissions from the use of urea in road transport are calculated based on an estimation of the total consumption of AdBlue. The AdBlue consumption is calculated based on estimations on the share of vehicles using SCR-catalysts and the unit consumption of AdBlue per unit of fuel. The AdBlue consumption in Finland in 2016 was estimated to 25 000 ton, corresponding to CO_2 emissions of 5 900 ton [94]. These CO_2 emissions should be added to the total TTW and WTW GHG emission calculations, described by equations 14 and 15.

6.2 Vehicle efficiency and the real-world driving factor

The vehicle efficiency and fuel consumption are measured in certain test conditions, that try to replicate the conditions of real-world driving. However, it has consistently been proven that the emissions and fuel consumption measured in the test are too low [77]. In the model, this discrepancy between test conditions and real-world driving conditions is accounted for using a real-world driving factor (η_i). The real-world driving factor has been quantified through fuel consumption measurements in real-world driving of large vehicle fleets. Tietge et al. [77] has reported a real-world driving factor of 9 % for vehicles with model year 2001, and then a gradually increasing factor to 42 % for vehicles with model year 2015. These are also the real-world driving factors used in a Norwegian vehicle fleet and emission model by Fridström [90]. The real-world driving factor used in the Finnish model Lipasto is 15 % [94]. In the Matero model the real-world driving factor is only needed for passenger cars and light commercial vehicles, as the energy consumption slopes of these vehicles are derived from the reported CO_2 emission values. The energy consumption slopes for heavy-duty vehicles and buses are derived from the Handbook Emission Factors for road transport HBEFA, which already considers real-world driving conditions [91].

Real-world driving factors that are used in the model are based on the values in Tietge et al. [77], but further adjusted for country-specific conditions. The adjustments are made in order for the total fuel consumption in the model to match the total fuel consumption reported in the country. These adjustments factors are further described in Kilpeläinen [6], as well as adjustment factors for heavy-duty vehicles and buses. As the purpose of the model is to calculate the emissions from the vehicles registered in each of the countries, the data on total mileage is considered to be reliable, and changes are rather made to the efficiency. However, vehicles can drive and fill up the tank in other countries than the country it is registered in, which causes an inconsistency when modeling the fuel consumption from the national vehicle fleet. For the purpose of the model, it is considered that the amount of fuels from abroad, consumed by a national vehicle fleet equals the amount of fuels that vehicles from abroad consume in that country. Based on information on cabotage in the Sweden, it could be considered that vehicles from outside Sweden consume more fuel at Swedish fueling stations, than Swedish vehicles consume at fueling stations outside Sweden [95]. Similar patterns could be analyzed in the other countries, but this is left out of the scope of this study.

The country-specific energy consumption adjustment factors (a) and real-world driving factors are presented in Table 10. All real-world driving factors are considered to be constant from 2016 and onwards. Energy consumption of Finnish gasoline vehicles are adjusted to be 20 % lower, which gives a real-world driving factor of 14 % in 2016. Diesel powertrain energy consumption is reduced with 6 %, resulting in real-world driving factor of 33.5 %. The real-world driving factor for other powertrains in Finland is set to 42 % in 2016.

Table 10 Energy consumption adjustment factors ($\boldsymbol{a}$) and real-world driving factors ($\boldsymbol{\eta_i}$) for passenger cars and light commercial vehicles in 2016 and onwards.

	Finland		Sweden		Norway	
Powertrain	a	η_i	a	η_i	a	η_i
Gasoline	-20 %	14 %	-14 %	22 %	-10 %	28 %
Diesel	-6 %	34 %	0 %	42 %	0 %	42 %
Other	0 %	42 %	0 %	42 %	0 %	42 %

As mentioned, reliable information on emissions and fuel consumption of plug-in hybrids is still scarce. In the NEDC test method, PHEVs show emission reductions of around 70 % compared to a similar gasoline or diesel vehicle. According to vehicle test made by Figenbaum [96], the emission reduction is more likely to be around 50 %. The share of electric driving is the determining factor of the emission for PHEVs. Ligterink and Smokers [97] report real-world fuel consumption from a fleet of PHEVs based on information from fuel card provider in the Netherlands. The share of electric driving was reported to be between 6-39 %, depending on the PHEV model. The average for all vehicles was 29

%. For the same model, the electric driving share in the NEDC test method is 50-86 %, which significantly reduce the emissions and energy consumption. In the Matero model, an electric driving share of 55 % is used, based on survey results from Norwegian PHEV drivers [22]. As the capacity of PHEV batteries is increasing and charging becoming easier and more available, a higher share of electric driving could be considered in the future, which would also contribute to lower CO_2 emissions.

7 Total driven mileage and transport need used in the model

As national road transport is modeled using the national vehicle fleet, the total driven mileage by these vehicles is one of the most important parameters. Driven mileage is obtained from odometer readings from vehicle inspections, as described in the next section. An average mileage is calculated for each vehicle segment, describing how much a typical vehicle in that segment drives annually. The average mileages are used as inputs in the model, which can be seen in Figure 21 and equation 12. Multiplying the average mileage of each vehicle with all vehicles is in the fleet, gives the total mileage driven by the whole fleet, which is relevant for energy and emission calculations.

For the future, the driven mileage cannot be based on meter readings. Instead, national transport need forecasts are used, as described in section 7.2. The average mileages for the vehicle segments are assumed to remain unchanged. For PC and LCV, the forecasts are made directly for total driven mileage. HDV transport need is more complicated, and the transport need is modelled through transport work. Transport work is the transported tons times driven mileage. The transport need for buses is modeled as passenger work, that is, number of passengers times driven mileage. Transport need for the HDV and bus segments are further elaborated in Giacosa [7].

7.1 Total driven mileage and parameter average mileage

In Finland, Sweden and Norway, vehicles must pass periodical vehicle inspections. The odometer reading is collected during these inspections and can be used as a reliable source for estimating total mileage driven by the vehicles. Since 2014, the EU Commission has required that the odometer readings must be collected, as stated in the directive EU 2010/48. All vehicles in the national vehicle registers, or that have been in the register at any point of the year, are included in this data. This excludes vehicles that are not registered to drive on roads, and military vehicles that belong to the states [98].

All vehicles do not, however, go through the periodical vehicle inspection every year. Passenger cars are inspected for the first time after three years in Finland, the next time when the vehicle is five years and after that every year. [99]. Similarly, in Sweden PC and LCV are required to be inspected for the first time at the age of three, the next time at the age of five and after that every year. However, if the vehicle is a commercial vehicle, such as a taxi or a leasing vehicle, the vehicles are inspected every year. Buses and HDV are also inspected every year. [100]. In Norway, the regulation requires passenger cars to go through their first inspection in the fourth year, after which they are inspected every second year. Utility vehicles are on the other hand required to be inspected in the second year, and after that every year. [101]. It is important to notice that the regulation on vehicle inspections is subject to change, and e.g. in Finland new regulation will be in place after 20.5.2018 which will require PC to be inspected for the first time at the age of four, after that every second year and vehicles older than ten years every year [99].

The estimated share of vehicles that are covered by annual inspections is 59 % in Finland, 65 % in Sweden and 75 % in Norway [98], [101], [102]. For vehicles that do not have an odometer reading during a specific year, the average mileage is taken from a similar group of vehicles, and thus the average mileages and total mileages is always an approximation. Some vehicles are not in the register the whole year, such as new registered vehicles, deregistered vehicles and temporarily deregistered vehicles and the dates for the odometer readings are distributed over the whole year. Because of this, a daily mileage is calculated for each vehicle based on the last two odometer readings and the number of days between these readings. The daily mileage is after that multiplied with the number of days the vehicle has been in traffic during that year to obtain the vehicles total mileage. [98].

Average mileages obtained from the odometer readings, are assigned to each of the 17 Matero model sub-segments, and further broken down by powertrain and age. For the Swedish model, the 2012-2016 vehicle fleet SCB data including the mileage, was used to obtain the average mileage for each powertrain sub-segment and aged. [32]. The Norwegian vehicles' average mileages are derived from SSB data on vehicle mileage [101]. For Finland, the total mileages divided into some segments are obtained from Statistics Finland [102]. The age distribution is, however, not detailed enough, so age distribution functions are created based on the Swedish data, and used for the Finnish average mileage values. Figure 22 presents annual vehicle mileage for some powertrains sub-segments as a function of age. In the first registration years, vehicles are on average only in the fleet half a year, as they are registered throughout the year. In the model, the vehicles are however thought to be in the fleet from the first day of each year. Due to this, the average mileage for the first year is set to be similar to the average mileage for year two.

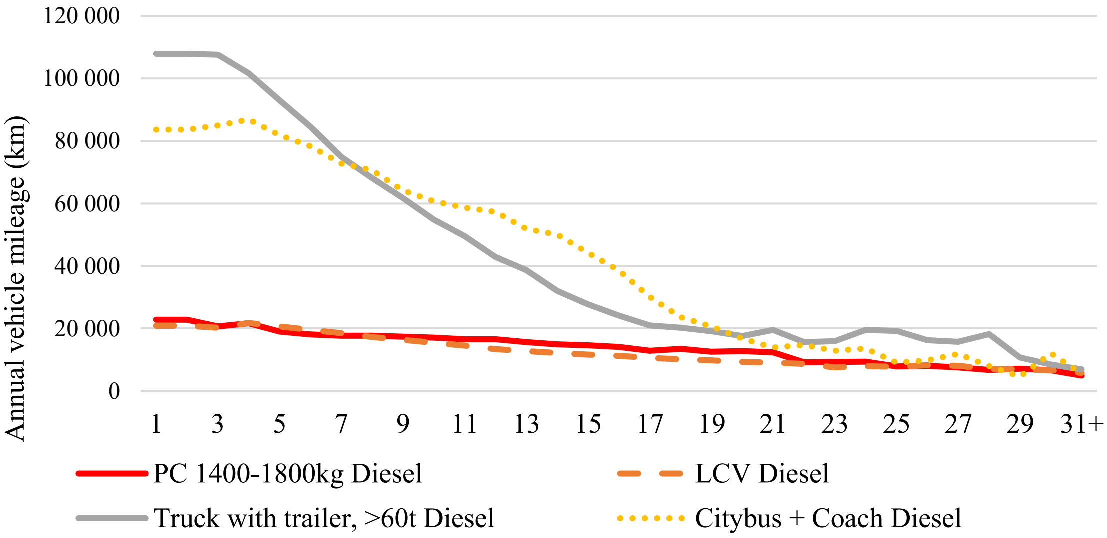

Figure 22 Annual mileage as a function of vehicle age in Sweden for various powertrain sub-segments used in the model [32].

Dividing the average mileages into detailed powertrain sub-segments and age categories, creates problems with small segments which can have extreme values. For many powertrains, there is not even any reliable mileage history, as such vehicles have not been in the fleet. For these powertrains, the total sub-segments average mileage is used. Specific powertrain average mileages are created for gasoline and diesel, and the rest of the powertrains use the total sub-segment average. In Sweden, specific average mileages are also created for CNG when the number of vehicles is large enough. Using the sub-segment average mileage for powertrains with low number of vehicles gives a good implication on the mileage and reduces randomness from small powertrain sub-segments. On the long-term, it is considered to be reasonable to think that the mileage from different powertrains are close to the average, as the limiting factor often is the need of covering a distance, and that need is considered to remain similar. Especially for HDV, it is also not likely to that one powertrain would have significantly lower average annual mileage, as that dramatically increases the cost per kilometer of that vehicle. Similar discrepancies on annual average mileage as seen for gasoline and diesel, can very well exist in the future, but with the information available at the moment, the average mileages of new powertrains are modeled as the sub-segment average.

As previously described, the differentiation between a citybus and a coach is not very straightforward. For the Swedish model the total mileage for each bus segment is taken from the SCB vehicle mileage data [32]. In 2016 the average mileage for a citybus was 67 000 km, 62 000 km for a coach and 33 000 km for a minibus. For the Finnish and Norwegian model, the mileage allocation between citybus, coach and minibus is an estimation. In Finland, data is available separately for buses in commercial and public traffic, as well as separated into buses with 10-42 seats and buses with more than 42 seats. [102]. There are very few old citybuses in Finland, which increases the average mileage of the sub-segment. In Finland, the average mileage in 2016 for a citybus was 86 000 km, 60 000 km for a coach and 28 000 for a minibus. In Norway, SSB collects data on vehicle mileage and number of passenger from the municipalities for public routes and from the companies for commercial routes [103]. SSB has determined routes in advance that are completely in urban areas, and buses driving on these routes can be classified to drive as citybuses [104]. Dividing the mileage on routes that are completely in urban areas with the number of vehicles classified as citybuses, gives the annual average mileage of citybuses in Norway. The annual average mileage in 2016 for a citybus was 62 000 km, 41 000 for a coach and 22 000 for a minibus.

7.2 Transport need assumptions

National forecasts on transport need are used to create a base scenario for future transport, thus estimating how much will be driven in the future. For PC and LCV, the transport need forecast is made on total vehicle mileage and for HDV and Buses on transport work. For HDV the transport work is described as transported ton kilometers of goods, and for Buses as transported passenger kilometers. See Giacosa [7] for further insights on the transport work forecast used in the Matero model.

In 2014 the Finnish transport agency published a national forecast on transport need development until 2030 and 2050 [105]. The national forecast is made with the Finnish transport agency mileage statistics from 2012 as a starting point. This total mileage is considerably higher than the total mileage received from the odometer readings, as presented in Figure 23. The transport agency's mileage statistics is created using automatic measurement and traffic counting services. There were around 470 automatic measurement stations on fixed important road traffic locations. The counting service utilizes microwave radar detectors, and divides the road network into around 15 000 homogenous road parts and 3 000 ramps. [106]. In 2016 the calculation method of the Finnish transport agency was adjusted, and the resulting difference in estimated mileage diminished. The two statistics are, however, not directly comparable, as the odometer readings give information on mileage from vehicles registered in Finland, independent on where they drive. On the contrary, the transport agency's statistics describe mileage on Finnish roads. As a result of these factors, the mileage from the odometer readings are considered more reliable and are used in the model.

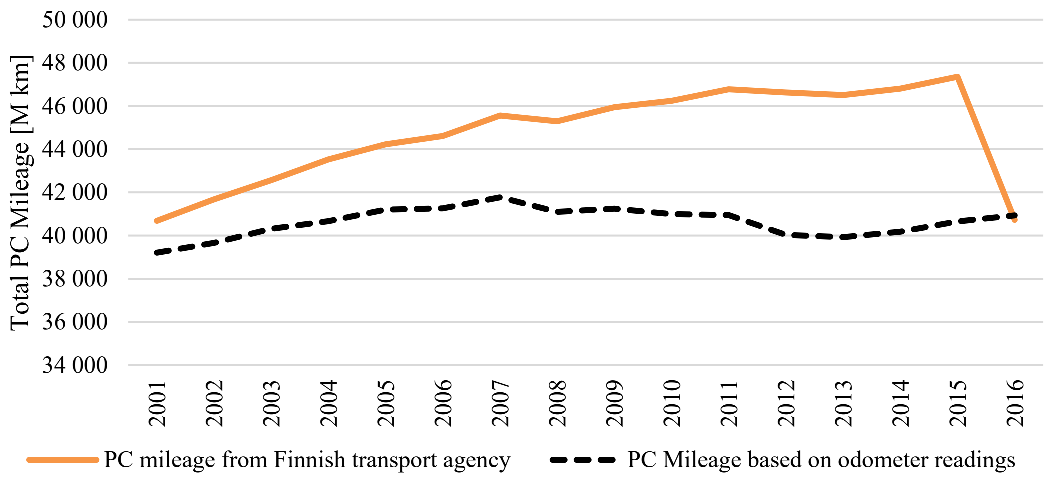

Figure 23 Total PC mileage as reported by the Finnish transport agency and based on odometer readings [102], [107].

The total forecasted mileage for all vehicle segments in Finland is presented in Table 11. The Finnish national forecast on transport need forecasts a growth in PC mileage of 26 % from 2012 to 2030, and 36 % to 2050 [105]. The forecast for PC has been proven to be too high, as the actual mileage between 2012-2016 has been significantly lower than the forecasted mileage as presented in Figure 24. VTT adjusted the forecast in the end of 2015 resulting in 12 % growth until 2030 and 16 % growth until 2050 for PC mileage [94]. This adjusted forecast is used to calculate the total mileage for PC and LCV in 2030 and 2050. The growth in transport need is then calculated using actual Finnish transport agency reported mileage numbers for 2015 as a starting point. The mileage growth is considered to be linear between 2015 and 2030, respectively 2030 and 2050. The mileage growth for each year is calculated with equation 17. Annual growth percentages are then calculated for each year and segment, which subsequently are used to calculate base assumption forecasted mileage used in the model, corresponding to the green line in Figure 24. The total PC mileage including values for Sweden and Norway, is presented in Figure 25 and the PC and LCV mileage development indexed for year 2016 is presented in Figure 27.

$$annual\ mileage\ increase = \frac{total\ mileage\ target\ year - total\ mileage\ year\ i}{target\ year - year\ i} \tag{17}$$

Table 11 Transport need growth factors from 2012 to 2030 and 2050 [105]

Segment	2030	2050	Unit for %-change
PC	1,12 (1,26)	1,16 (1,36)	kilometer
LCV	1,06	1,11	kilometer
HDV	1,06	1,17	ton kilometer
Bus	1,06	1,11	passenger kilometer

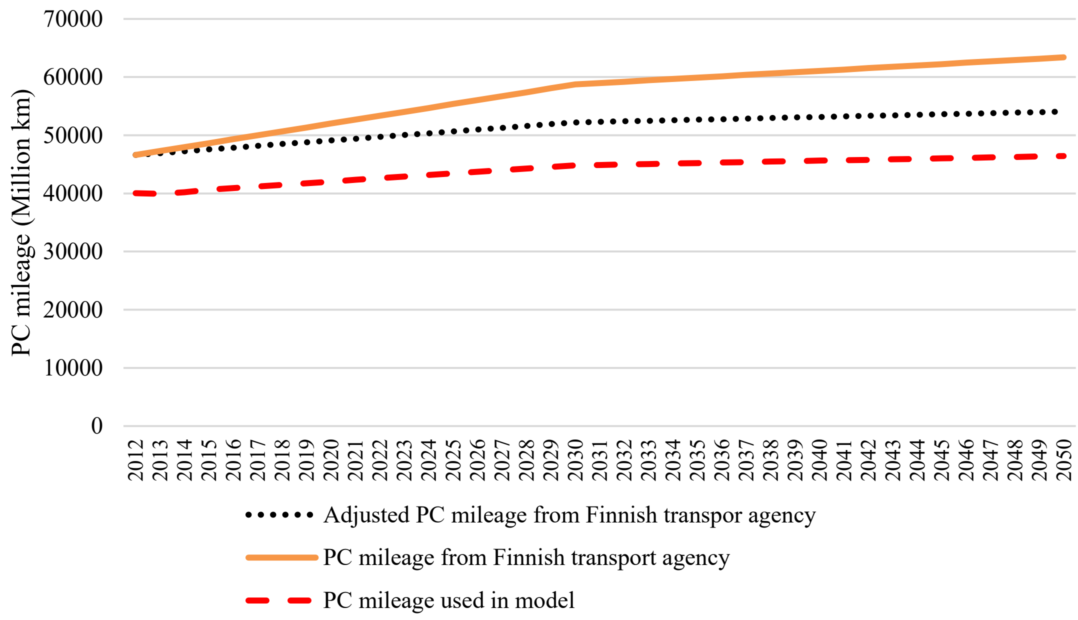

Figure 24 PC mileage forecast used in the model as well as the mileage forecast from the Finnish transport agency [105] and as adjusted by VTT [94].

In Sweden the Swedish Transport Administration's forecast is used to estimate the forecasted transport need [108], [109]. Figure 26 presents the total forecasted mileage for all vehicle segments. For PC the forecast is made on passenger kilometer development. As the number of passengers in a passenger car is considered to remain constant in the model methodology, the growth factor for passenger kilometers equals the growth factor for mileage. The same method as for the Finnish transport need forecast is used to calculate the annual growth factors for Sweden. There is no specific forecast for LCV, so the PC growth factors are used for LCV. The total PC mileage is presented in Figure 25 and PC and LCV mileage development indexed for year 2016 is presented in Figure 27.

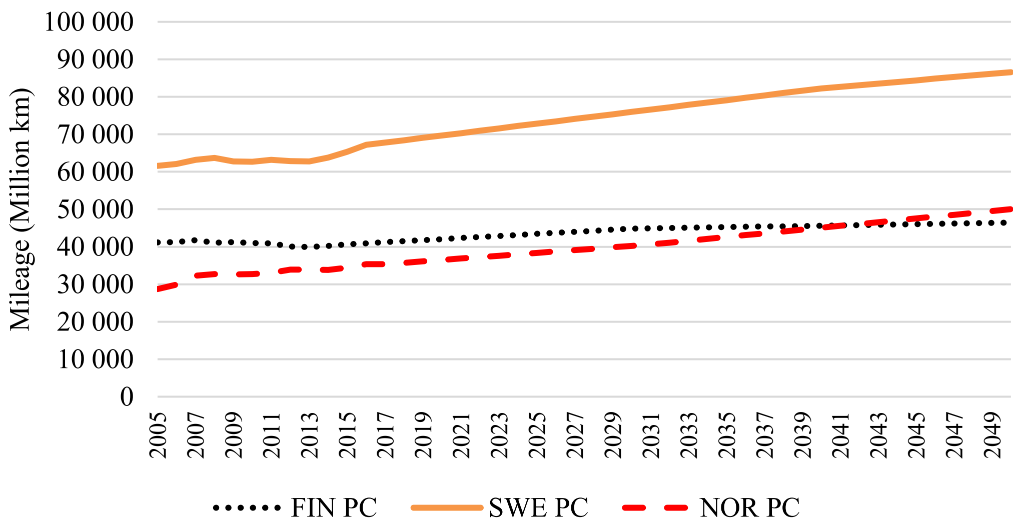

Figure 25 Total historical and forecasted mileage for PC and LCV in Finland, Sweden and Norway until 2050.

The forecasted total mileage in Norway is also presented in Figure 26. The mileage is based on national travel demand projections and forecasts for Norwegian freight transport [110], [111]. This forecast corresponds with the assumptions used in the Norwegian national transport plan [5] and the TØI report Vehicle fleet forecasts based on stock-flow modeling [90]. PC mileage is presented in Figure 25 and PC and LCV mileage development indexed for year 2016 is presented in Figure 27.

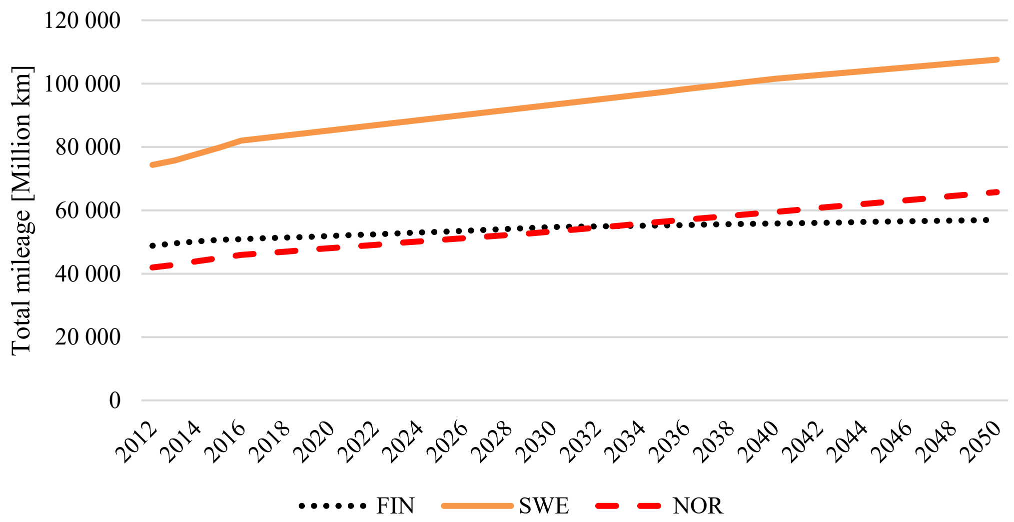

Figure 26 Total mileage for all vehicle segments. Mileage for years 2012 to 2016 are based on mileage statistics and 2017-2050 on national forecasts.

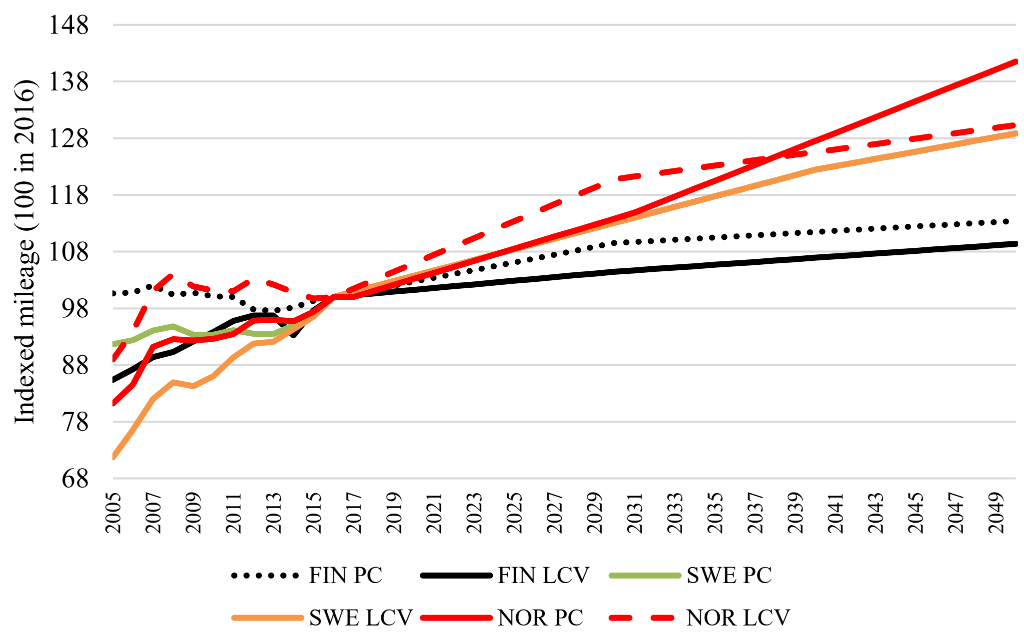

Figure 27 Transport need development for PC and LCV in Finland, Sweden and Norway. Indexed as 100 for the value of 2016.

8 Historical fuel consumption used to test the model

Quantifying GHG emissions and energy demand from road transportation with a bottom-up approach as in the Matero model is a complex task, due to the large number of factors affecting the road transport system. To ensure that the bottom-up model gives reliable results, the results can be compared to statistics on national fuel consumption in road transportation. This was done for the years 2012-2016 in the Matero model. Fuel consumption was calculated using the methodology in Figure 21 and if the modelled fuel consumption did not match the statistical, input parameters were revised. The adjusted parameters and further elaborations on model reliability are found in Kilpeläinen [6]. In the next sections, the method for obtaining statistics on national road transport fuel consumption is explained.

8.1 Fuel consumption in Finland

The total amount of fuels used in road transport in Finland, is based on national statistics on energy consumption in transport as reported by Statistics Finland [112]. The same data is also used in the VTT Lipasto model [94], which in turn is used in the Finnish national inventory report on greenhouse gas emissions. In Finland, those who operate on the fuel market, have to report total amount of sales and energy content [113]. The share of the fuels that are used in road transport, is based on an allocation process, where VTT has created sub-models to account for fuels used in other sectors [94].

The fuel market operators, do also have to report specific amounts of biofuels. These are used when calculating the fulfillment of the Finnish biofuel mandate [114]. Even though the biofuels are reported as detailed components, publicly available information is only on the three categories biogasoline, biodiesel and biogas. Information on the specific components are confidential, due to the market competition situation [115]. For the liquid biofuels between 2012 and 2016, it is assumed that all biodiesel is HVO and all biogasoline is ethanol. This conclusion has been drawn from an analysis on the reported fuel components as reported for the calculation of energy from renewable sources according to Directive EC 2009/28 [116].

On the Finnish market, there are two grades of gasoline available. These are the common grade 95 E10, with up to 10 vol% ethanol, and the protection grade 98 E5, with up to 10 vol% ethanol. In 2016 the volumetric share of 98 octane E5 was still, 35 %, which is considerably higher than the share in Sweden and Norway [117]. The explanation to this is that certain vehicles have problems with higher shares of ethanol in the fuel, and therefore use 98 E5. Partly it is also explained by customers' beliefs, and not actual facts. These vehicles are typically old, and as they leave the fleet, the share of 98 E5 decreases. This has been seen the last years, and since 2012, the 98 E5 share has come down from 45 vol% to 35 vol%. On the Swedish and Norwegian markets, E10 has not yet been introduced, and thus, the share of 98 octane fuel is much lower. The amounts of E85 is retrieved from the Finnish Petroleum and Biofuel Associations statistics on sales of fuel products. It is assumed that all of the E85 is used in the road sector [117].

Since 2005 there have been two different types of diesel on the Finnish market. In 2005 a new product was introduced, which is called non-road gasoil. This fuel is technically the same as autodiesel, but it has lower taxes and includes an Euromarker additive to enable monitoring of illegal use. The autodiesel is used in road transportation and also leisure boats, since the beginning of 2008. The non-road gasoil is used in non-road vehicles, machinery, railway transport and domestic navigation. Additionally, there is also a third gasoil, which is called light fuel oil and used for heating and stationary combustion. [118]. The allocation of autodiesel and gasoline on the Finnish market is presented in Figure 28.

In 2015 the road transport segment in Finland consumed a total of 154 TJ of gas, used in CNG vehicles. Of this 83 TJ was biogas, which makes the bioshare of energy 54 %. Since 2012 there has not been a clear trend on increasing or decreasing consumption of gas in road transport, but the amount of biogas has dramatically increased, from 15 TJ in 2012. [112]. There is not assumed to be any consumption of LNG so far on the Finnish market, which is why consumption of electricity and hydrogen is based on the Matero model bottom-up estimation.

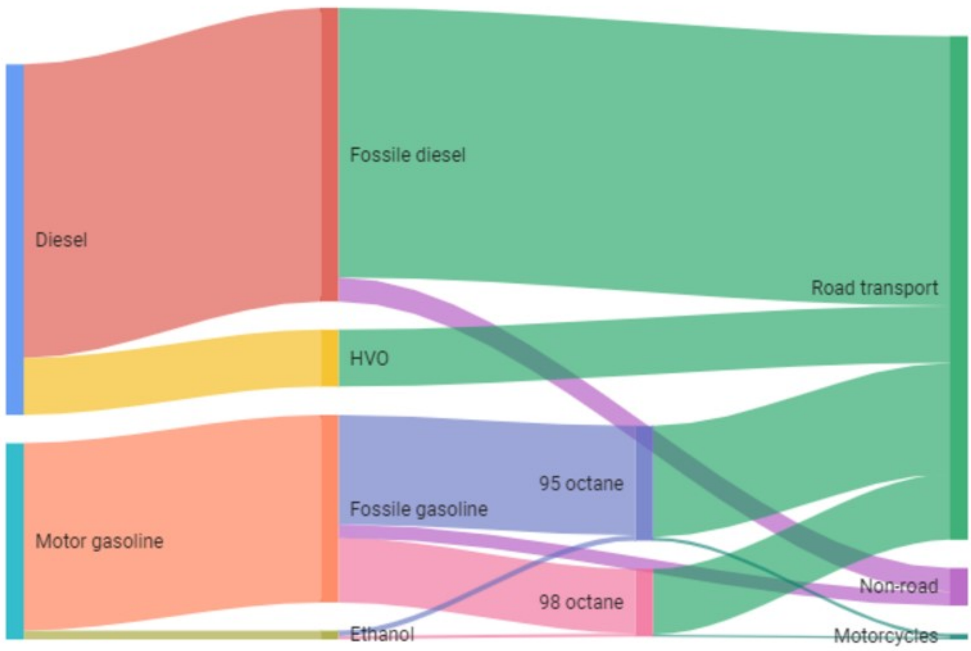

Figure 28 Flows of autodiesel and gasoline on the Finnish fuel markets in 2015.

8.2 Fuel consumption in Sweden

In Sweden, the total amount of fuel components is provided by the national statistics on supply and delivery of petroleum products as reported in the SCB quarterly fuel statistics [119]. These amounts are then allocated to different user categories using a similar method as in the Swedish National inventory report 2017 on greenhouse gas emissions [120]. The total delivered amount of gasoline includes low blended ethanol. Apart from low blends, ethanol is also used as E85 and ED95. In these statistics, the amount of ethanol is representing both ethanol and the renewable component in ETBE. These two are combined as one group, as no specific statistics are publicly available.

In the last years, the gasoline in Sweden has been a mixture of around 5 vol% ethanol and 95 vol% fossil ethanol. For the allocation of gasoline to different user sectors, the amount of low blended ethanol is first reduced from the total delivered amount of gasoline. From the amount of fossil gasoline, the amount used by military is subtracted, as well as the estimated amount of consumption from leisure boats, off-road vehicles and machinery. The remaining fuel for transport on road, is then divided into 95 octane and 98 octane, according to the share of delivered fuels as in the quarterly fuel statistics. In the last years, the share of 98 octane gasoline has been lower than 4 % of the total gasoline deliveries. It is assumed that all the ethanol is consumed in the road transport sector. This is not reflecting the actual situation, but the incentives for biofuel blending are for the road transport sector, and therefore the biofuels are supposed to be used there.

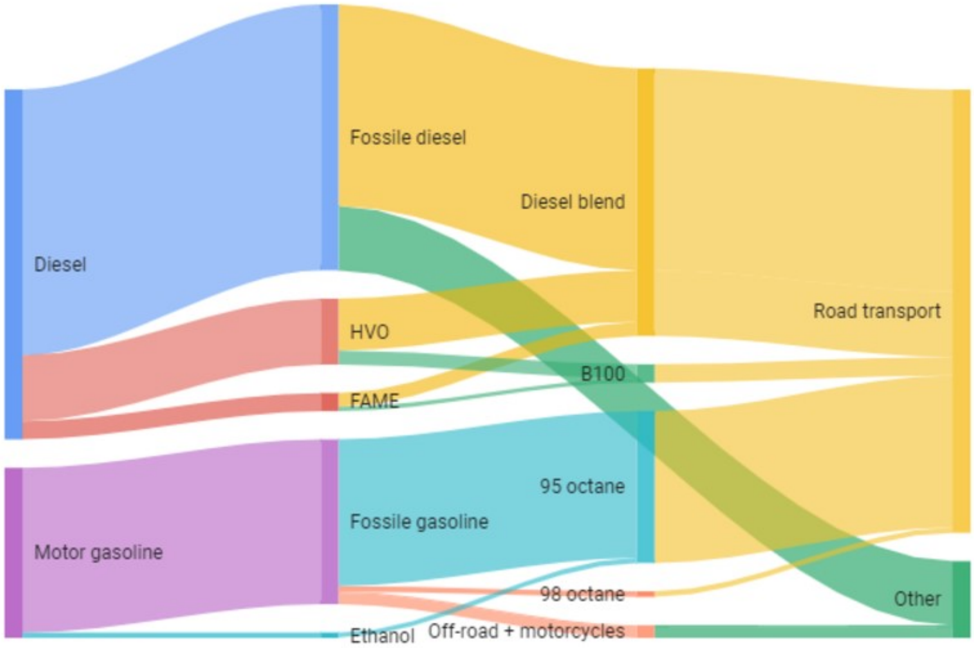

Figure 29 Amount of auto diesel and motor gasoline in Sweden 2016 used in road transport or other segments.

The total amount of natural gas and biogas is based on the SCB national statistics on deliveries of motor fuel gas and data from the Swedish energy agency [121], [122]. The share of biogas has increased dramatically in Sweden and was 73 % in 2016. Still, the amount of biogas is expected to increase. There is no reliable statistics available on the consumption of electricity and hydrogen, and therefore the Matero model bottom-up results are used directly as such, without any modifications for discrepancies between model results and actual fuel sales. Data on the amount of electricity used in transport is available, however, the major part of this electricity consumed is in rail transport, and therefore is not usable as such for the estimation of electricity used in road transport. Since vehicles can be charged at home, and wherever electricity is available, the best way of estimating electricity consumption in road transport is a bottom-up approach as used in this study.

8.3 Fuel consumption in Norway

The total fuel consumption for the road transport segment in Norway has also been estimated from total sales of fuels minus use in other segments. The sales of fuels are retrieved from the SSB Sales of petroleum products statistics [123]. For gasoline, a top-down approach is used where other consumption of gasoline is from use in e.g. mopeds and motorcycles, small boats, motorized equipment and snowmobiles [124]. The consumption of ATV is only included In Norway diesel is separated into auto diesel charged with auto diesel tax, and tax-free diesel used for heating and machinery. The consumption of diesel in road transport is estimated as all the auto diesel charged with auto diesel tax [125]. This differs from the method used in the Norwegian National Inventory report for

Greenhouse gas emissions where diesel in road transport is estimated as all auto diesel, with a two percent addition counting for assumed use of tax-free diesel in road transport [124]. However, the Statistics Norway's energy balance numbers are considered more reliable and are therefore used as input in the model [126]. The liquid biofuels used in Norway consist of HVO, FAME ethanol and some ethers. Amounts of biofuels are estimated based on data from data delivered from the Norwegian Energy agency [127]. It is assumed that all biofuels are used in the road transport segment and mopeds and motorcycles.

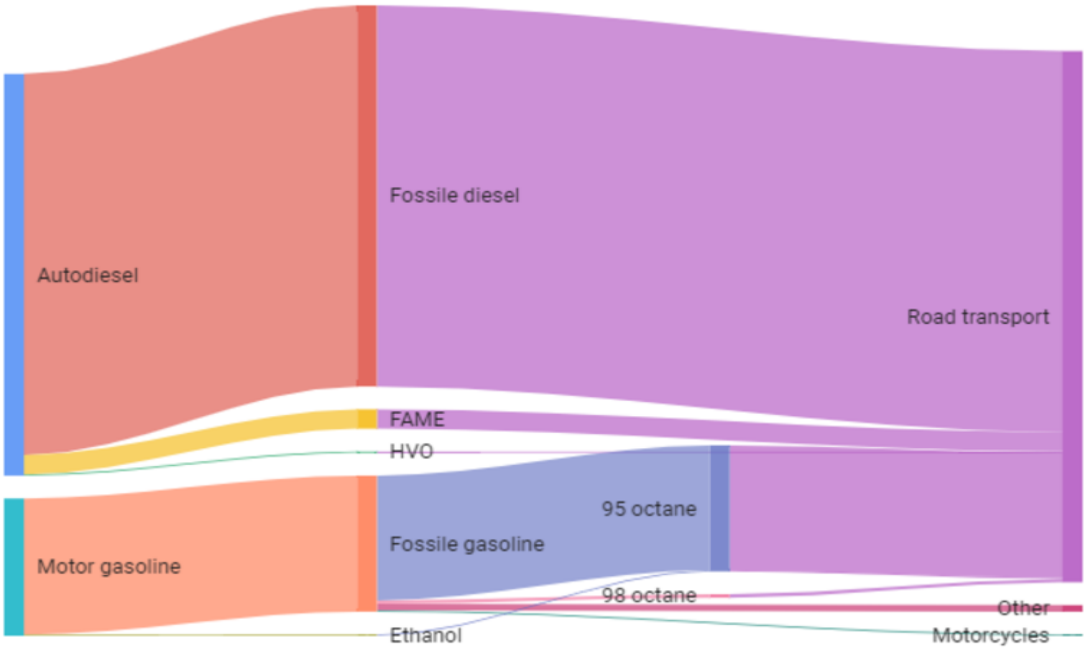

Figure 30 Amount of auto diesel and motor gasoline in Norway 2015 used in road transport or other segments.

The estimation on use of natural gas and biogas is based on a bottom-up approach, where the consumption of fuel is a result from the emission model of the Handbook Emission Factors for road transport HBEFA [124], [125]. There are no reliable statistics available on the consumption of electricity and hydrogen, and therefore the model results are used directly as such, without any modifications for discrepancies between model results and actual fuel sales.

9 Scenarios for fuel composition and share of biofuels

The previous chapter explained how statistics on fuel consumption were obtained, to be used to check for the reliability of the bottom-up model for years 2012-2016. For the future, scenarios had to be created for the share of different fuel components, especially considering the share of biofuels. The fuel scenarios and energy factors were used to obtain fuel consumption from energy consumption, as illustrated in Figure 21. Existing national targets and regulations related to fuel components were considered to obtain the fuel scenarios described in this chapter.

The fuel scenario determines the percental shares of different components comprising the eight energy carriers used in the model for 2017 to 2050. The model is able to account for ten different gasoline components, eight diesel components and two components for CNG, LNG and hydrogen. All energy carrier components and their respective GHG intensities are found in Appendix 1. Due to the large differences in GHG intensity among the different components, the fuel scenarios have a large impact on the total road transport emission in the model. The difference in GHG intensity is mainly depending on whether the component is a biofuel or not. As mentioned in chapter 6.1, the TTW GHG emissions of biofuels are calculated as zero, which makes the GHG intensity of biofuels much lower. On a WTW basis, biofuels are considered to provide 70 % GHG emissions reductions compared to the corresponding fossil fuel. Thus, the fuel scenarios are mainly scenarios for the share of biofuel for the energy carriers.

A base, a low and a high fuel scenario were created for each of the three countries. The scenarios are presented in appendix 3. The low scenario refers to a low share of biofuels, the high scenario to a high share of biofuels and the base scenario to a share of biofuels between the low and the high scenario shares. For each country, the base scenario is made to comply with applicable regulation and targets set by the governments. EU regulation sets certain requirements for Finland and Sweden, mainly through the Fuel quality directive (FQD) (EC 2009/30) [128], Renewable energy directive (RED) (EC 2009/28) [92] and Indirect land use change directive (ILUC) (2015/1513) [129]. The Fuel quality directive enforces the fuel supply industry to achieve a minimum 6 % GHG intensity reduction of road transport fuels by 2020 compared to 2010. Additionally, the directive defines sustainability criteria for biofuels. The Renewable energy directive sets requirements on the renewable energy share of transport fuels used in EU member states. The minimum renewable energy share in EU member states should be 10 % by energy in 2020, however, the target is further specified on country level. The renewable energy share in road transport is calculated as the sum of biofuels and renewable electricity divided by the sum of all fuels including electricity.

Biofuels that are compliant towards the RED directive needs to fulfill sustainability criteria specified in Articles 17 and 18 of the RED. As of January 2017, biofuels need to provide GHG reductions of 50 % in order to fulfill the sustainability criteria. Note that biofuels are considered to provide on average 70 % GHG reductions in the model, as this is more reflecting the historical situation in the countries in question and it is assumed that sustainability criteria are going to increase. Sustainability criteria are further specified in the ILUC directive. The ILUC directive sets a maximum level of 7 % from conventional biofuels and a target of at least 0.5 % advanced biofuels. Conventional biofuels are often also called first-generation biofuels, and comprises biofuels made from crops grown specifically for the production of biofuels. Conventional biofuels are typically produced from vegetable oil and sugar or starch obtained from the feedstock. Complexity is added to the calculation of the renewable energy share in transport, as certain biofuels can be considered twice towards national obligations. This method is typically referred to as double counting, and concerns compliant biofuels produced from wastes, residues, non-food cellulosic material and lingo-cellulosic material.

The biofuels that are considered in the scenarios are mainly ethanol in gasoline, FAME and HVO in diesel and biogas, as these were the main biofuels also in 2016. FAME can be used in up to 7 % by volume in diesel, for higher biodiesel shares the use of HVO is required (EN590). This limits the amount of FAME in road transport to 7 % of the diesel consumption, unless fuels like B100 are used. B100 is a diesel fuel consisting of 100 % FAME, and requires a modified engine. B100 is used in Sweden, especially in buses, but is not included as a separate fuel in the model. The share of FAME in 2016 was approximately 7 % in Sweden, 5 % in Norway and 0 % in Finland, according to the analysis in the previous chapter. In the fuel scenario, it is assumed that share of FAME in all three countries will reach a level of 7 % in a few years, gradually increasing from the current share. All additional biodiesel is assumed to be HVO.

The European standard EN 228 sets a volumetric maximum limit of 10 % ethanol in gasoline. The fuel 95 E10 that is distributed in Finland contains up to 10 % ethanol, while gasoline with more than 5 % ethanol still is not distributed in Sweden and Norway. Even though the amount of ethanol typically is slightly lower than limits in fuel sales, they are considered to be 10 % and 5 % in the model. A rapid introduction of E10 in Sweden and Norway is assumed in the fuel scenarios, resulting in that most of the gasoline is E10 already in 2022. The share of 98 octane gasoline is assumed to decrease by a factor of 0,98 annually. Furthermore, an introduction of E20 is considered in 2025. E20 is a blend of 20 vol% ethanol and 80 vol% fossil gasoline. Derived from the Finnish electric scenario outputs, the share of mileage from new gasoline vehicles is 5,9 % in 2025 of the total mileage driven by gasoline vehicles. In the fuel scenarios, it is assumed that almost all new gasoline vehicles use E20, which roughly corresponds to 5 % of the total gasoline consumption. The share 5 % is used instead of 5,9 %, to account for the higher efficiency of new vehicles and the fact that all vehicles will not be able to use E20. Thus, the share of E20 in gasoline is set to be 5 % in 2025, and after that increased according to equation 18, where i refers to the years 2026-2050, and g the share of E20 of total gasoline.

$$g_i = g_{i-1} + 0{,}05 \cdot (1 - g_{i-1}) \tag{18}$$

9.1 National biofuel policies and mandates as a base for the fuel scenarios

The bio-share in Finland is regulated through the Finnish biofuel mandate [114]. The mandate forces fuel suppliers to ensure a renewable energy share of 12 % in 2017, 15 % in 2018, 18 in 2019 and 20 % in 2020 and onwards. The mandate is set on the energy share of the distributed gasoline, diesel and biofuels. Assuming that the maximum amount of 7 % is covered by conventional biofuels, 13 % is left for advanced biofuels. As the advanced biofuels can be considered twice against the obligation, the actual energy share need only be 13,5 %. In addition to the biofuel mandate, the Finnish government has set a target of 30 % physical renewable energy share in 2030 in the transport sector [3]. The base scenario presented in Figure 31 is made to comply with these obligations.

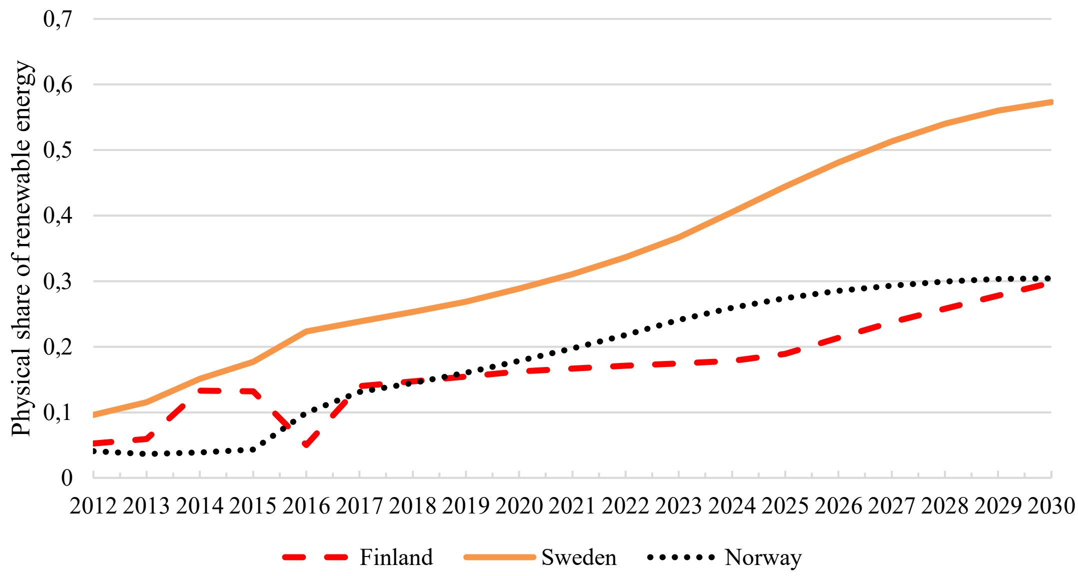

Figure 31 Physical share of renewable energy in liquid and gaseous fuels in Finland, Sweden and Norway. Base scenario for 2017-2030, historical values for 2012-2016.

In Sweden, the physical energy share of biofuels was above 20 % already in 2016. The renewable share of diesel was roughly 31 %, 3,3 % of gasoline and 72 % of CNG. This makes Sweden the country in EU, with the highest renewable share in transport fuel, both related to the physical energy share and according to calculation method used in the RED. [131]. The Swedish base fuel scenario is based on the policy proposal for a reduction duty by the Swedish government [132]. Reduction duties are outlined to benefit biofuels with high GHG reduction. The policy would entitle fuel suppliers to contribute to a reduction in GHG emissions, by distributing biofuels. The reduction duties would consist of reduction quotas, that would increase stepwise towards an indicative GHG reduction target of 40 % in 2030. The policy is proposed to be enforced from the beginning of 2018, with initial reduction quotas being 2,6 % for gasoline and 19,3 % for diesel. In 2020 the respective quotas would be 4,2 % for gasoline and 21 % for diesel. Other energy carriers would be left out of the policy, and it would be specifically designed to reduce the emissions of gasoline and diesel, in contrast to the EU regulation.

For the reduction duty policy, the reduction quotas would be defined as one minus the lifecycle emissions of biofuels and fossil fuels divided by the lifecycle emissions if only fossil fuels were used to obtain the same amount of energy. This way biofuels with low lifecycle emissions contribute more to the fulfillment of the duty, in contrast to an obligation exclusively on physical energy share or volumetric blending. [4]. Based on the reported lifecycle emissions of biofuels used in Sweden in 2016, the reduction duty in 2018 could be fulfilled by blending 6,5 % ethanol by volume in gasoline and 7 % FAME and 17,7 % HVO in diesel. This would roughly add up to a 25 % volumetric biofuel share of diesel and gasoline combined. [133]. To achieve the 40 % GHG reduction target, assuming sustainable biofuels with 70 % GHG savings, the biofuel physical energy share should be 57 %. To achieve this for 2030 in the base fuel scenario, the volumetric share of ethanol in gasoline is assumed to be 14 %, and the volumetric share of FAME and HVO in diesel to be 7 % and 73 % in 2030. Ethanol used in E85 is included in the ethanol share of gasoline.

Norway has largely adopted the Renewable energy directive, Fuel quality directive and the ILUC, even though the country is not part of EU. Regulation related to biofuels in road transport is defined in *"produktforskriften"*, also referred to as product regulation. [134]. The product regulation sets a blending requirement on fuel suppliers, similar to the biofuel mandate in Finland. However, the Norwegian blending requirement is calculated on a volume basis, and not as the physical energy share. In the last version of the product regulation, the blending requirement was set to be 8 % starting from October 2017, and increases to 10 % in 2018. Additionally, the share of advanced biofuels shall be at least 2,5 % in 2017 and 3,5 in 2018. [135]. A minimum requirement of 4 % ethanol in gasoline starting from 2017 is also included in the product regulation. The Norwegian government has further decided to extend the blending requirement to 13 % in 2019 and 20 % in 2020, with requirements on advanced biofuels of 2,25 % in 2019 and 4 % in 2020. [5].

In 2016 the blending requirement was 5,5 %, and starting from 1.1.2017 it was 7 %. As the requirement changed to 8 % in October, the requirement for 2017 is 7,25 % [135]. From the beginning of 2017 the blending requirement is calculated as the quota between the volume of liquid biofuels and the sum of volumes of gasoline, diesel and liquid biofuels. Previously. biogas could be counted towards the requirement, but is excluded as from 2017. The advanced biofuels shall be produced from wastes, residues, non-food cellulosic material and lingo-cellulosic material, as in accordance with the ILUC directive. Advanced biofuels can be double counted towards the total blending requirement, but not towards the requirement on advanced biofuels or ethanol in gasoline. [136]. The fuel scenario for Norway in Figure 31, follows the share of biofuels laid out in blending requirement, and additionally physical bioenergy share to 30 % in 2030 to contribute to emission reductions. However, there is no current regulation that would oblige suppliers to achieve the 30 % biofuel energy share in 2030.

10 Vehicle fleet, GHG emissions and fuel consumption results

In this section, scenario results from the Matero model are presented. Emphasis is on quantifying the evolution of energy consumption and GHG emissions, as a result of certain road transport development scenarios. As described in previous chapters, scenarios have been created for the vehicle fleet, energy carriers, transport need, average vehicle mileage and vehicle loads. Here some of these scenario results are presented, in addition to insights on the vehicle fleet evolution and GHG emission reduction potential. Results for the total vehicle fleets are also presented, even though the bus and HDV scenarios are presented in Giacosa [7].

10.1 Passenger cars and inertia of the vehicle fleet

The passenger car vehicle fleet in the electric scenario is presented in Figure 32. The vehicle fleet in both the electric and conservative scenario are found in Appendix 2. Differences in the powertrain split for the future vehicle fleets, are directly related to the actual fleets in 2016, scenarios for powertrain shares, new vehicle sales and net-flow intensity rates as described in chapter 4. As seen in picture Figure 32, the share of BEV and PHEV is gradually increasing in the vehicle fleets, which can be related to the electric scenario powertrain splits in Figure 15. Noteworthy is, that the share of diesel vehicles increases until 2020, as the shares of diesel in the powertrain scenarios are still on historically high levels, which is illustrated in Figure 33. In the electric scenario, conventional gasoline and diesel vehicles are replaced by BEVs, PHEVs and HEVs. Sales of other powertrains are low, which results in that such powertrains are slowly diminishing from the fleet, e.g. flexi-fuel vehicles in Sweden. The share of BEV in 2030 is 11 % in Finland, 17 % in Sweden and 28 % in Norway. Similarly, the share of PHEV is 7 % in Finland, 12 % in Sweden and 18 % in Norway.

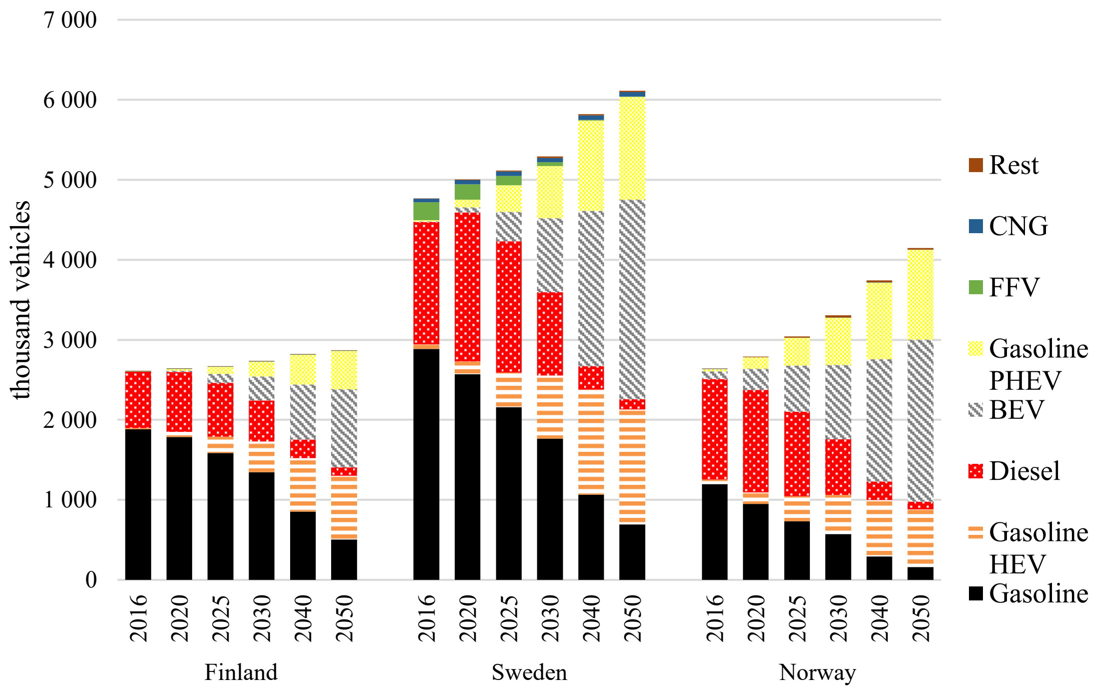

Figure 32 Electric scenario passenger car vehicle fleet in Finland, Sweden and Norway by powertrain 2016-2050.

The number of vehicles in the fleet is a result of the stock-flow-cohort methodology for vehicles leaving the fleet, and new vehicle sales from the scenarios for powertrain share and transport need forecasts. The stock-flow-cohort model uses net-flow intensity rates to estimate the flow of vehicles in and out of the fleet for all vehicles that are not registered for the first time in a vehicle register. As the net-flow intensity rates are fairly similar between the three countries [6], the main differences in the fleet evolution is a result of differences in scenarios for powertrain shares and national transport need. The passenger car transport need, the forecasted total mileage driven by passenger cars, is increasing significantly faster in Sweden and Norway compared to Finland according to the national forecasts [105], [110], [137]. Higher total mileage means that more vehicles need to be added to the fleet, in order for the vehicle fleet to drive the same amount as the total forecasted mileage.

The increased number of vehicles is also partly explained by the comparably higher average mileage of diesel vehicles. The average mileages of diesel passenger cars used in the model, are on average around 20 % higher than the BEVs, PHEVs and HEVs. As the share of diesel vehicles are leaving the fleet, a result is that a higher number of new vehicles are needed to drive an equal amount. Additionally, the average mileage of passenger cars is slightly decreased for the next few years, which also adds to the number of required vehicles in the fleet. Unless the average mileage would be adjusted, the number of new passenger cars coming into the vehicle fleet would drop dramatically in the next years. With these adjustment, the share of new vehicles is slightly higher than without the adjustment, which results in a marginally higher fleet efficiency.

Instead of decreasing the average mileage, the total mileage in transport need scenario could also have been increased, or the new vehicle sales could have been left on a low level. The impact of the average mileage adjustments and subsequent higher new vehicle sales on fuel consumption and emissions is minor, as the fuel consumption and emissions are more dependent on the total mileage. The increasing forecasted total mileage, new powertrain split and adjusted average mileage results in that the number of passenger cars in the vehicle fleet is growing by 5 % in Finland, 11 % in Sweden and 25 % in Norway between 2016 and 2030. Total mileage of passenger cars is modeled to increases with 10 % in Finland, 13 % in Sweden and 15 % in Norway in the same time interval.

Comparing the diffusion of technologies such as mobile phones to that of powertrains in the vehicle fleet, the diffusion of powertrains in the vehicle fleet is much slower [78]. This is a result of the large inertia of the vehicle fleet, which in this case, inertia refers to the slow renewal of the vehicle fleet. The large inertia of the vehicle fleet is noted when comparing to the powertrain scenarios in Figure 15, and the corresponding electric scenario passenger car vehicle fleets in Figure 32. Highlighting this phenomenon, the share of BEV is 30 % of new passenger cars in the Finnish electric scenario in 2030. However, the share of BEV is only 11 % in the passenger car vehicle fleet in 2030. This is a result of the fact that vehicles are used for many years before they are renewed. In the 2016 vehicle fleet, the average age of passenger cars was 11.9 in Finland, 10.0 in Sweden and 9.8 in Norway. Of the four vehicle segments, passenger cars are on average the oldest, followed by heavy-duty vehicles, light commercial vehicles and buses. The average age of vehicles is the highest in Finland for all vehicle segments, resulting in a slower fleet renewal of the Finnish vehicle fleet. The inertia of the vehicle fleet can also be described by the fact that more than 20 % of passenger cars in the 2016 Finnish fleet are older than 17 years. If this is to continue, 20 % of the vehicles registered in 2017 will still be in the fleet in 2034.

Inertia of the vehicle fleet can also be explained with the help of Figure 33, where passenger cars in the Finnish electric scenario vehicle fleet in 2030 are presented by registration year and powertrain. The registration year is related to the age of the vehicle so that a vehicle with the registration year 2030 is one year old and a vehicle with registration year 2020 is ten years old. It is worth noticing that the vehicle fleet in Figure 33 is the same as the fleet depicted by the powertrain share bar for the Finnish fleet in 2030 in Figure 32. From the age distribution, it can be seen that most old vehicles are gasoline vehicles, as the share of diesel in new registrations previously was lower. The number of vehicles with registration year 2016 and earlier are a result of actual vehicle fleet data from 2016 and the flow of vehicles caused by the net-flow-intensity rates. For vehicles with registration year 2017 and newer, the amount is derived from new vehicle sales scenarios and flow of vehicles caused by the net-flow-intensity rates.

Larger amounts of BEVs, PHEVs and HEVs are seen in the fleet with registration year 2017-2030 as a result of the electric scenario powertrain split. This way, the diffusion of new powertrains and their gradual impact on the total vehicle fleet are also depicted. Of the vehicle fleet presented in Figure 33, 49 % are gasoline vehicles, 19 % diesel vehicles, 11 % BEVs, 7 % PHEVs, 14 % HEVs. However, powertrain shares of vehicles in a fleet, do not directly relate to the energy consumption of the respective energy carriers. Some vehicle types are typically driven more, and older vehicles drive less, as describes in section 7.1. The passenger car average mileage as a function of vehicle age is plotted on the right axis Figure 33. This way, the larger impact on mileage from newer vehicles is illustrated.

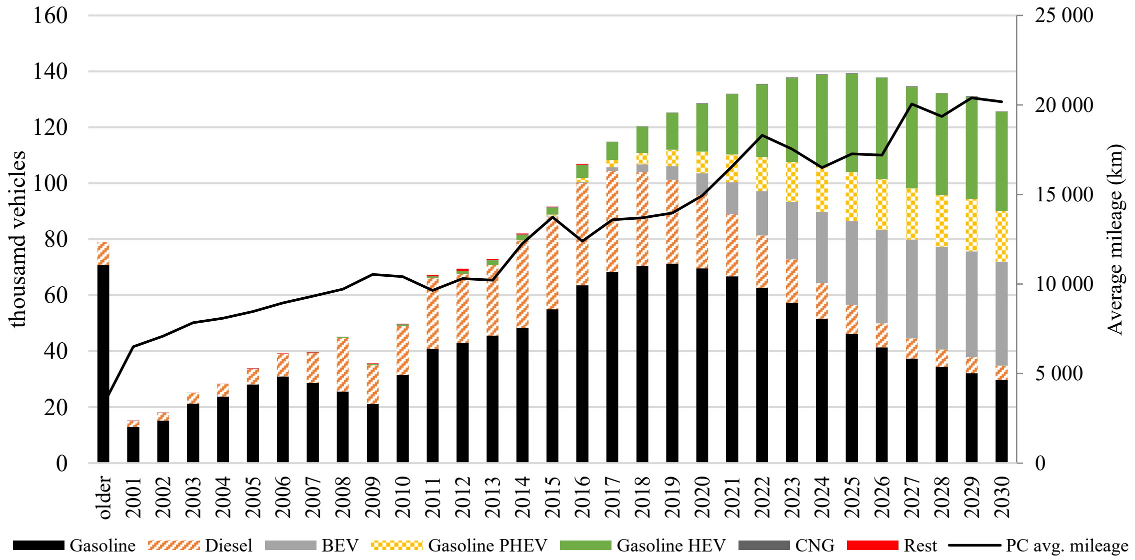

Figure 33 Electric scenario passenger car vehicle fleet in Finland 2030 by registration year and powertrain plotted on the left axis. Passenger car average mileage as a function of vehicle age (registration year) plotted on the right axis.

10.2 Passenger car energy consumption and GHG emissions

The development of energy consumption is mainly a result of how much is driven and the efficiency of the vehicles. For the electric and conservative scenario, the efficiency in the electric scenario is higher, as there are more BEVs and PHEVs, that is, vehicles with higher efficiencies. As the energy consumption of a BEV is set to be 26 % to that of a conventional gasoline vehicle, these vehicles are reducing the energy consumption with 74 %. In the Finnish electric scenario, there are 160 000 more BEVs than in the conservative scenario, and 74 000 more PHEVs. The total energy consumption of passenger cars in Finland by powertrain in the electric and conservative scenarios is presented in Figure 34. In the electric scenario, the share of energy consumption by BEV is 5 %, whereas it is 2 % in the conservative scenarios. These shares can be related to 11 % of the fleet being BEV in 2030 in the electric scenario and 5 % in the conservative scenario. As previously described, the energy consumption should rater be related to the mileage than the number of vehicles. The share of mileage by BEV is 13 % in the electric scenario and 6 % in the conservative scenario.

In the Finnish electric scenario, the passenger car energy consumption decreases with 17 % between 2016 and 2030, compared to 11 % in the in the conservative scenario. For the Swedish scenarios, the respective reductions are 22 % in the electric scenario and 15 % in the conservative scenario. For Norway, the energy consumption decreases with 22 % in the electric scenario and 11 % in the conservative scenario. Taking a closer look at the results from the Finnish model, it is seen that the share of diesel vehicles in the passenger car powertrain scenarios is decreasing, which causes the energy consumption of to decrease. In the electric scenario, the diesel consumption by passenger cars is decreasing from 42 PJ in 2016 to 31PJ in 2030 and 15 PJ in 2050. A similar, but slower, trend is seen in the conservative scenario. The energy consumption of gasoline from passenger cars was 56 PJ in 2016, and is 46 PJ in 2030 in the electric scenario and 48 PJ in the conservative scenario. The reduction in gasoline is much smaller compared to the reduction in diesel, as the sales of gasoline vehicles is decreasing slower, and most PHEVs and HEVs are considered to have a gasoline engine.

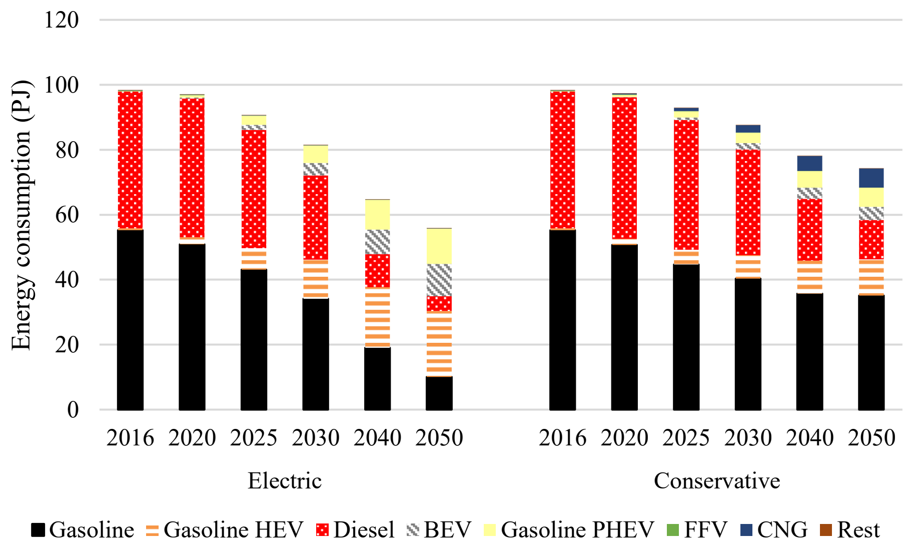

Figure 34 Energy consumption of passenger cars in the electric and conservative scenario in Finland by year and powertrain.

In all scenarios energy consumption shifts from fossil fuels to electricity and biofuels. To assess the impact of this shift, primary energy demand or GHG emissions could be considered. The WTW and TTW GHG emissions are analyzed in this study to assess the impact of the change in energy consumption on the environment. Development of WTW emissions from passenger cars 2016 to 2050 in the electric scenario is presented Figure 35.

Low WTW emissions of electricity in all three countries, provide significant benefits to the use of BEVs and PHEVs. In the model, the 2016 emission factor for electricity in Finland is 41 $gCO_2eq./MJ$, in Sweden 4 $gCO_2eq./MJ$ and 0 $gCO_2eq./MJ$ in Norway. The emission factors are modelled to gradually decrease in Finland and Sweden, as the share of renewable energy is expected to increase. Comparing the emission factors to the average emission factor for an EU electricity mix, here considered to be 165 $gCO_2eq./MJ$ [138], the comparable benefit of BEVs and PHEVs is evident. Here the EU electricity mix refers to electricity consumed in the European Network of Transmission System Operators for Electricity (ENTSO-E) area. To assess the impact of the electricity WTW emissions, the electricity emission factor was set to 165 $gCO_2eq./MJ$ in the Norwegian model for the year 2016. The emissions from electricity generation is expected to decrease in the EU, and this was accounted for by linearly increasing the additional renewable electricity share to 40 % in 2030, resulting in an emission factor of 99 $gCO_2eq./MJ$ in Norway in 2030.

With the higher electricity emission factor in Norway, total WTW emissions would increase as illustrated with the striped part of the bars in Figure 35. This part is directly related to the GHG emissions of electricity, as the original emission factor was zero. The WTW emissions of passenger cars in Norway is reduced by 17 % between 2016 and 2030, from 7100 ktonCO2eq. to 5870 ktonCO2eq, with the higher electricity emission factor. The similar values with the emission factor being zero are 6830 ktonCO2eq. in 2016 and 4430 ktonCO2eq in 2030, reflecting a 35 % total WTW emission decrease. The impact of the electricity emission factor depicts the fact that results from one country cannot be directly transferred to other countries, without assessing the input values and assumptions.

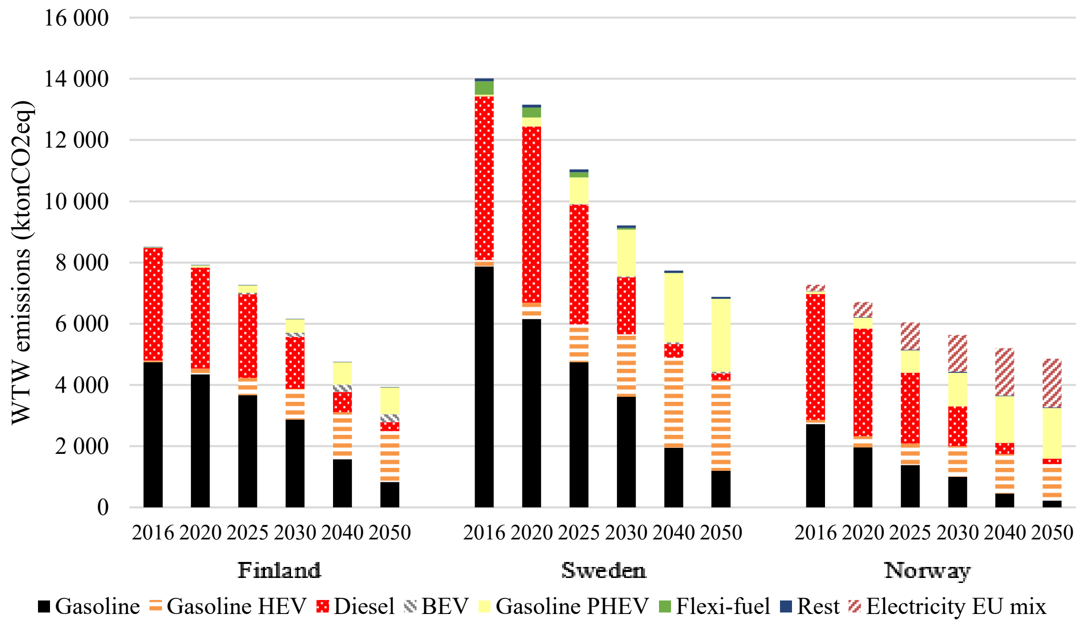

Figure 35 WTW emissions in $gCO_2eq./km$ from passenger cars in the electric scenario. The emissions are divided by powertrain. The striped parts for the Norwegian bars represent the additional WTW emissions of PCs in Norway, if the average electricity emission factor of EU (165 $gCO_2eq./MJ$) is used instead of the Norwegian emission factor (0 $gCO_2eq./MJ$).

10.3 Modelled total vehicle fleet

After the detailed assessment of passenger cars, the other vehicles in the fleet do also need to be addressed when assessing road transport energy consumption and GHG emissions. Obtaining values directly from the Finnish model and the modelled situation in 2016, light commercial vehicles made up 10 % of the vehicle fleet, 11 % of the total mileage and 11 % of the total WTW emissions. Heavy-duty vehicles made up 3 % of the vehicle fleet, 7 % of the total mileage and 25 % of the total WTW emissions. Similarly, buses accounted for 1 % of the vehicle fleet, 1 % of the total mileage and 4 % of the total WTW emissions. The rest was covered by passenger cars, accounting for 86 % of the vehicle fleet, 81 % of the total mileage and 60 % of the total WTW emissions. The proportionally larger share of emissions and mileage by HDV and buses is worth noticing, in spite of the small share of the vehicle fleet.

As a short summary on the HDV segment, the vehicles are divided into the sub-segments Truck with trailer, Tractor unit with semitrailer and Other. These segments are then further divided into three weight segments. The segments have significantly different characteristics, but here they will all be considered as one single group. Heavy-duty vehicles made up 2 % of the total vehicle fleet in numbers in Sweden in 2016 and 2 % in Norway. As seen in Figure 22, the annual mileage is higher for HDVs compared to the other segments. Of the total national mileage in 2016, 6 % arose from HDVs in Sweden and 5 % in Norway. HDVs are also heavier than the other vehicle segments, which result in that the average fuel consumption is roughly six times higher than an average passenger car. Combining the higher mileage and higher fuel consumption, the HDV segment is responsible for a significant share of road transport energy consumption and emissions, in spite of the mediocre share in number of vehicles. Buses are divided into citybuses, coaches and minibuses. The differentiation between a citybus and a coach is in many cases quite challenging, as the differentiation is a result of what type of driving the vehicles are performing. In this study, the differentiation of citybuses attempts to reflect that citybuses are driving exclusively in urban traffic, whereas the other buses are driving both on highways and in urban areas.

Regarding the powertrain share development, LCVs are largely following the same development trend as passenger cars, although with slightly lower electrification and slower phase-out of diesel. The scenarios and development of heavy-duty and bus segments are described in Giacosa [7]. Results related to vehicle fleet development, energy consumption and GHG emissions can be found in Appendix 2, Appendix 4 and Appendix 5. Diesel is expected to remain the dominant powertrain in HDVs and coaches, due to its superior energy density. Problems related to NOx emissions from the diesel powertrain can be controlled with SCR-systems in these large vehicles. As the cost of the SCR-system is relatively low to the total cost of HDVs or coaches, it is feasible to install it, which is not the case for smaller and cheaper passenger cars and light commercial vehicles. Examining the split between powertrains in the Norwegian electric scenario HDV vehicle fleet in 2030, approximately 93 % of the vehicles are diesel, 4 % diesel HEVs, 1 % diesel PHEVs, 1 % running on gas and 0,5 % FCVs.

The powertrain split in Finland and Sweden are even more relying on the conventional diesel powertrain. Considering the total bus segment vehicle fleet powertrain split, the Swedish electric scenario shows the highest share of electrification. In 2030, 78 % of the buses are considered to be conventional diesel vehicles, 14 % BEVs, 7 diesel HEVs and 1 % CNG vehicles. Electrification of buses is mainly taking place in the citybus segment. Citybuses are considered to offer great potential of cost-efficient GHG reduction through electrification, as the urban driving cycle suits the electric powertrain and that citybuses are used on predetermined routes, which enables planning for charging availability. Apart from the citybuses, the HDVs and other buses are considered to remain dependent on the diesel powertrain with some hybridization in certain applications.

In the efficiency improvement scenario, the annual efficiency improvements for HDVs and buses is considered to be around half of the efficiency improvement of PCs and LCVs up to 2021. The lower efficiency improvement in these segments, is a result of lack of regulation on gCO_2/km for HDVs and buses. After 2021, the annual efficiency improvements are decreasing year by year in a similar manner to the scenario for PCs and LCVs. Efficiency improvements in the HDV segment can be thought to be driven by cost savings from an improved fuel economy. As no regulation is in place that forces manufacturers to improve the efficiency, as is the case for PCs and LCVs, only such efficiency improvements will be made that provide a more cost-efficient option to customers. HDV efficiency can also be improved in respect to emissions per tonkilometer, and the current trend of increasing vehicle size is expected to increase, which reduces the emissions per transported ton of goods. Giacosa [7].

As a combination of new powertrains and improved energy efficiency, the energy efficiency is increasing for all vehicle segments in the model. Comparing the per kilometer energy consumption (MJ/km) of new registration between 2016 and 2030 in the Finnish electric scenario, the reduction is 44 % for passenger cars, 26 % for LCVs, 10 % for HDVs, 32 % for citybuses and 9 % for the other buses. Furthermore, heavy-duty transport work is modelled to increase with 12 % in Finland, 32 % in Sweden, and 34 % in Norway between 2016 and 2030 [105], [109], [111]. The large modelled increase is based on national forecasts on transport need, reflecting a forecasted population growth and increased economic activity. Mileage from buses is modelled to increase by 8 % in Finland, 10 % in Sweden and 3 % in Norway based on national forecasts on growth in passenger kilometers [105], [110], [137]. In the scenarios, the transport needs grows quite fast in all vehicle segments, and the share of the total mileage in each of the four segments remains fairly unchanged. The uncertainty regarding future transport need is high, and the impacts of a changing transport need growth is quantified in the sensitivity analysis in the following chapter.

Table 12 Share of energy consumption and WTW GHG emissions in the Finnish electric scenario in 2016, 2030 and 2050.

	2016		2030		2050	
	Energy	WTW	Energy	WTW	Energy	WTW
PC	60 %	60 %	57 %	52 %	49 %	51 %
LCV	11 %	12 %	12 %	17 %	12 %	11 %
HDV	25 %	25 %	27 %	27 %	34 %	33 %
Bus	4 %	4 %	4 %	4 %	4 %	4 %

A result of the faster decrease in energy consumption in the passenger car segment, compared to the heavy-duty segment, is that the share of energy used by HDVs increases and the share of PCs decreases. A similar effect can be seen for the WTW GHG emissions, but the emissions are directly dependent on the scenarios for biofuels. A higher share of biodiesel lowers the share of emissions from HDV, and increases the share from PC, as HDVs mainly are using diesel and the share of gasoline is higher in the PC segment. Shares of energy consumption and WTW GHG emissions are shown for the Finnish electric scenario in Table 12 for the years 2016, 2030 and 2050. The energy consumption share of HDV is increasing from 25 % in 2016, to 27 % in 2030 and 34 % in 2050. In the Swedish electric scenario, the HDV energy consumption share increases from 22 % in 2016 to 38 % in 2015. A similar relation is seen in the Norwegian electric scenario, where the share of energy consumption by HDV increases from 20 % in 2016 to 36 % in 2050. Considering that the diesel powertrain will remain dominant in the heavy-duty segment and that the total mileage will increase, increasing amounts of biodiesel are needed to reduce the amount of GHG emissions in heavy-duty transport. The increasing energy consumption in the HDV segment, will also keep the consumption of diesel on a high level for many years, even in the case of a rapid electrification of passenger cars. These conclusions can also be seen in Figure 36 and Figure 37, presenting the total road transport energy consumption by energy carrier and the volume on liquid biofuels in the electric scenarios for all three countries.

In the Finnish electric scenario, the total road transport energy demand from electricity is 1200 GWh in 2030 and 3300 GWh in 2050. This should be put in relation to concerns related to the increased demand of electricity from an electrification of road transport. The total electricity consumption in Finland was around 80 000 GWh in 2015 [139]. Thus, the total electricity demand from electric vehicles is proportionally very small compared to the total consumption, and such concerns are uncalled-for. Still, the electricity consumption from electric vehicles can have large impacts on local power grids and electricity peak demand. Utilizing electric vehicle charging as a balancing load, might provide large benefits to the stability of the power grid, and ensure low electricity prices for EV owners.

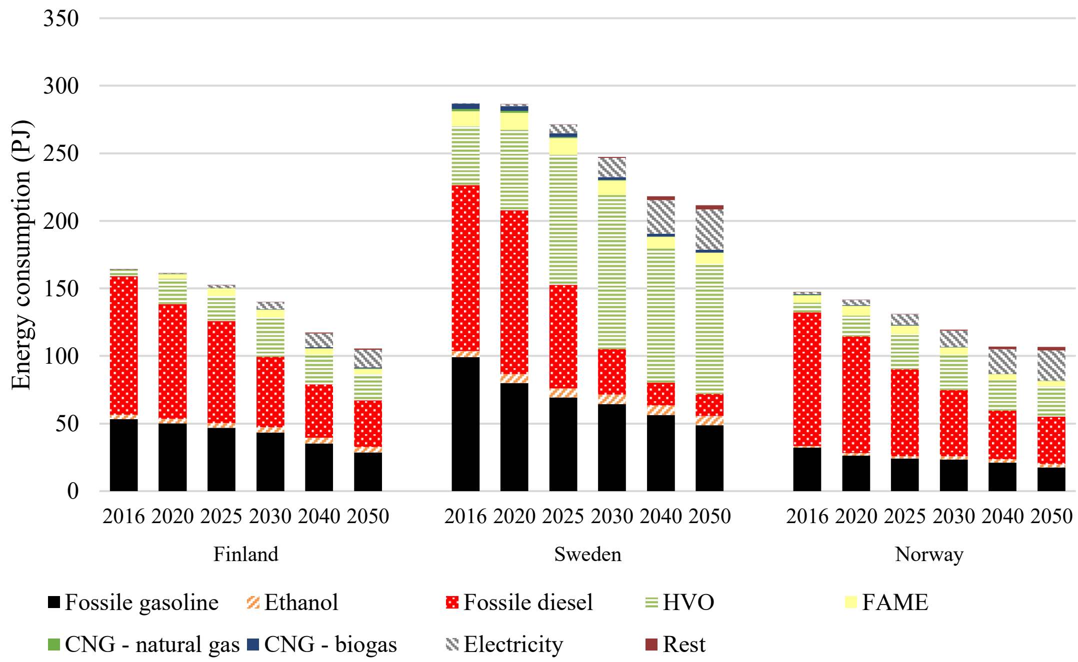

Figure 36 Total road transport energy consumption by energy carrier in the electric scenario.

Regarding the energy consumption of passenger cars, it was noted that the need of diesel as an energy carrier is diminishing in the electric scenario, as seen in Figure 34. Considering the whole vehicle fleet, the situation is significantly different. This can be seen from Figure 36, where the total road transport energy consumption is presented by energy carrier for the electric scenarios. Energy consumption is shifted from liquid fuels to electricity, mainly as a result of electrification in the PC, LCV and citybus segments. This shift contributes to a reduction in total energy consumption, as the electric powertrain is considered to be roughly four times more efficient. From the energy consumption, the total consumption of liquid fuels is calculated and presented in Figure 37. Perhaps one of the more interesting results is the high amount of required diesel, in this case the combined amount of fossil diesel, Fame and HVO, even in the electric scenario. The amount of gasoline will also remain on a high level for many years to come. From the perspective of GHG emission reduction, attention is drawn to the necessity of introducing E20, and especially E10 in Sweden and Norway, to allow for more biofuels in the road transport sector.

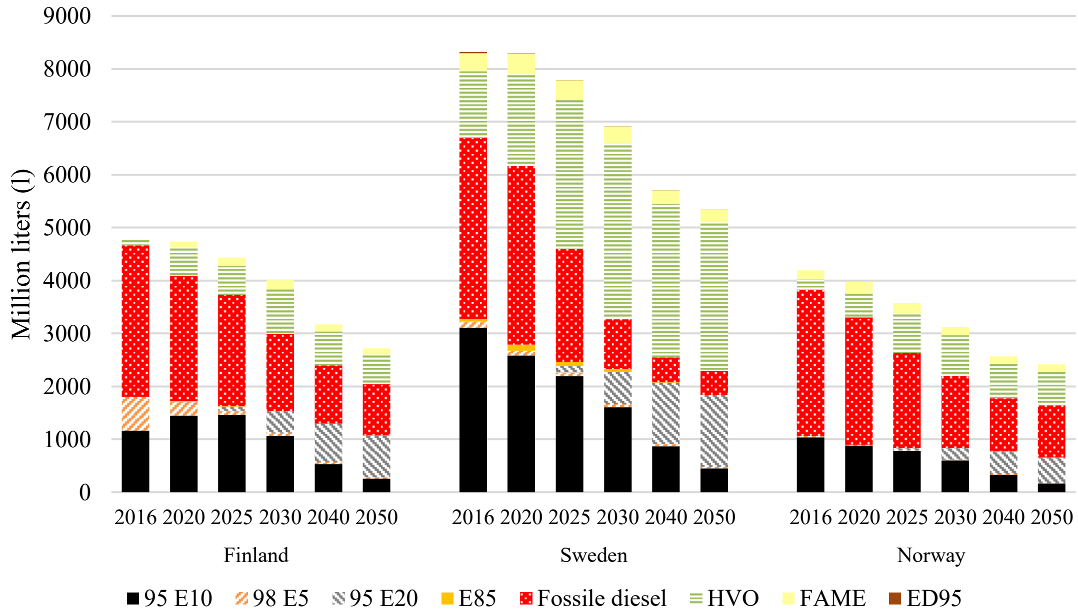

Figure 37 Liquid fuel consumption in Million liters. Values describing the electric scenario 2016-2050.

Finally, the total TTW GHG emissions are compared to the national GHG reduction targets for 2030 as described in the introduction. The obtained TTW emissions in the electric scenarios are presented in Figure 38, where the dotted lines represent the emission reduction target. Finland has set a target on 50 % reduction compared to 2005, Sweden on 70 % compared to 2010 and Norway on 55 % compared to 2015. With all the assumptions for the electric scenario presented previously in the study, none of the national reduction targets are met. In the assumptions, the total physical bioenergy shares of liquid and gaseous biofuels are 30 % in Finland, 57 % in Sweden and 30 % in Norway. In the Finnish scenario, the total number of BEVs and PHEVs is 495 000, when the target in the national climate and energy strategy is 250 000 [3].

The volumetric share of biodiesel is 41 %, but it would have to be 68 % for the scenario to reach the reduction target. That way the physical bioenergy share of liquid and gaseous fuels would be 45 %. In the Swedish scenario, the TTW emission reduction target would not be met, even with a 100 % volumetric share of biodiesel. A 100 % biodiesel share would result in a 67 % physical bioenergy share of liquid and gaseous fuels. In the case of a 100 % biodiesel share, most GHG emissions arise from gasoline, as electricity and all biofuels are considered not to emit any TTW GHG emissions. Thus, for example even more rapid EV diffusion or higher share of ethanol would be required to make the reduction target possible. In the case that the total transport need is set to remain on the same level as in 2016, thus excluding the forecasted transport need growth, a 98 % volumetric share of biodiesel would be enough to reach the reduction target. In the Norwegian electric scenario, a 71 % volumetric biodiesel share, corresponding to a 51 % physical bioenergy share of liquid and gaseous fuels, would be sufficient to reach the 55 % TTW emission reduction target. Considering that the transport need would grow according to the national transport need forecasts, the national GHG emission reduction targets seem to be very hard to reach. The reduction targets are very ambitious, especially when taking the inertia of the vehicle fleet into account. However, the reduction of emission continues after 2030, as the efficiency improves and electric vehicles make up a larger share of the vehicle fleet. This highlights the optimistic timeline for the national reduction targets.

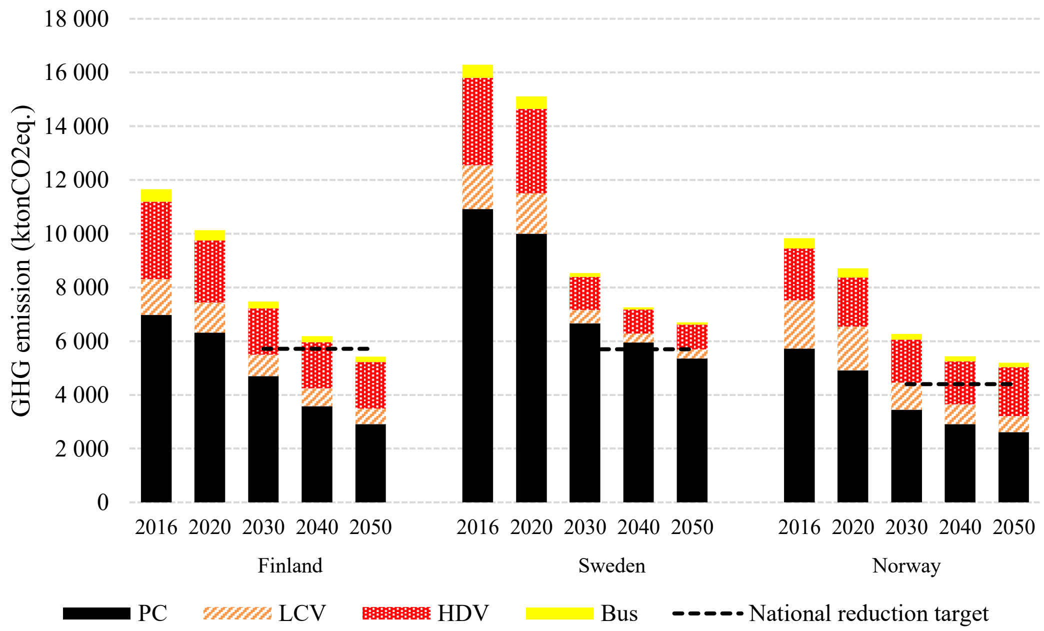

Figure 38 Electric scenario TTW GHG emissions and national road transport GHG emission reduction targets for 2030 as presented in chapter 1.

10.4 Sensitivity analysis

Model scenario output related to vehicle fleet, emissions and fuel consumption are results of a large set of assumptions, input values and simplified calculations. Understanding the causality of certain assumptions and scenario input values can be challenging, due to the complexity of the whole road transportation system and large number of parameters. By constructing and comparing scenarios, with changes made exclusively to a specific assumption, the impact of the change can be quantified. This way, a sensitivity analysis was performed on the modelled total TTW and WTW GHG emissions for the Finnish electric scenario in 2030. The assumptions varied were transport need growth, annual efficiency improvement and share of biodiesel. Additionally, a modified electric powertrain scenario was created where the number of passenger car BEVs is 200 000 in 2030, compared to 300 000 in the original electric scenario. This modified scenario for passenger car powertrain split is descriptively named 100 000 less BEV. As a base value, in each of the compared scenarios, is a biodiesel share of 0 %. Results from the scenario analysis are presented in Table 13 and Table 14. The biodiesel share is set as zero, as it has a large impact on emissions and the same biodiesel share in different scenarios does not necessarily result in the same amount of biodiesel.

Comparing the electric and conservative scenario, the conservative scenario results in 5 % higher emissions on a WTW basis and 6 % higher on a TTW basis. Extending the comparison to 2050, the respective differences would be 20 % and 23 %, which reflects the small change of powertrains in the vehicle fleet up to 2030, but larger impact year by year. The difference in TTW emissions is higher than in WTW emissions, as electricity is not considered to cause any emissions on a TTW basis. The modified electric scenario 100 000 less BEV results in only 1 % higher emissions both on a TTW and WTW basis, depicting the large measures needed to have an impact on the total road transport GHG emissions. Changing the annual efficiency improvement for new vehicles to 50 % of the base assumption, results in 3 % higher emissions in 2030. Similarly, increasing the annual efficiency improvement to 150 % of the base assumption, results in 3 % lower emissions.

The base assumption for annual efficiency improvement is a 13 % compounded efficiency improvement for new vehicles between 2016 and 2030. The 50 % scenario results in a 7 % compounded efficiency improvement and the 150 % scenario a 20 % improvement. Reduction in total road transport emissions is significantly lower, as the efficiency improvement only affects new vehicles entering the fleet. Of the parameters changed in Table 13, variation in the transport need growth has the highest impact on total emissions, as it immediately affects the total driven kilometers, and not only part of the fleet. This way, the significance of the total transport need is highlighted, when assessing the reduction potential of total GHG emissions in road transportation.

Table 13 Impact on the total TTW and WTW GHG emissions in the Finnish electric scenario in 2030 by varying scenarios, annual efficiency improvement and transport need growth.

Powertrain scenario	Transport need	Efficiency	Vol% biodiesel	WTW GHG (ktonCO2eq.)		TTW GHG (ktonCO2eq.)	
Electric	Base	Base	0 %	12 426		10 057	
Conservative	Base	Base	0 %	13 057	105 %	10 635	106 %
100 000 less BEV	Base	Base	0 %	12 544	101 %	10 177	101 %
Electric	Base	Base	0 %	12 426		10 057	
Electric	Base	50 %	0 %	12 768	103 %	10 329	103 %
Electric	Base	150 %	0 %	12 098	97 %	9 796	97 %
Electric	Base	Base	0 %	12 426		10 057	
Electric	150 %	Base	0 %	12 956	104 %	10 482	104 %
Electric	50 %	Base	0 %	11 918	96 %	9 648	96 %
Electric	0 %	Base	0 %	11 431	92 %	9 256	92 %

A 20 % biodiesel share has a larger impact on GHG emission reduction, than any of the variations in Table 13. The impact on GHG emissions from a certain volume of biodiesel, is presented in Table 14. Additionally, the amount of biodiesel needed to achieve the 50 % TTW GHG emission reduction target presented in chapter 1 is shown, both for the electric and conservative scenarios. These are referred to as the rows for electric target and conservative target in the table. As seen, 1,7 Million m^3 biodiesel is needed in the electric scenario and 1,9 Million m^3 in the conservative scenario. Introducing biodiesel has a direct impact on emissions, in contrast to efficiency improvement and new powertrains that only affect new vehicles. The emission reductions on a TTW basis are higher than on a TTW basis, as the TTW emissions of biodiesel are considered to be zero, and the WTW emissions are considered to be 30 % of fossil diesel.

Table 14 Impact on the total TTW and WTW GHG emissions in the Finnish electric scenario in 2030 by varying the share of volumetric share of biodiesel.

Powertrain scenario	Biodiesel volume (m^3)	Vol% bio-diesel	WTW GHG (ktonCO2eq.)		TTW GHG (ktonCO2eq.)	
Electric	0	0 %	12 426		10 057	
Electric	243 775	10 %	11 910	96 %	9 449	94 %
Electric	489 748	20 %	11 376	92 %	8 820	88 %
Electric	988 406	40 %	10 294	83 %	7 546	75 %
Electric	1 496 220	60 %	9 192	74 %	6 249	62 %
Electric	2 013 445	80 %	8 069	65 %	4 927	49 %
Electric	1 018 614	Base (41 %)	10 207	82 %	7 476	74 %
Electric target	1 701 967	68 %	8 745	70 %	5 723	57 %
Conservative target	1 939 984	71 %	8 861	71 %	5 695	57 %

The analysis related to the impact of certain scenarios on GHG emissions, can be extended to incorporate costs. In Table 15, the cost difference between the electric scenario and the modified electric scenario 100 000 less BEV is assessed for GHG emissions in 2030. This assessment is merely a simplified calculation example on how model results can be used to evaluate cost-efficient options for GHG emissions in road transportation. The biodiesel share in the electric scenario is kept at 41 %, in accordance with the base fuel scenario, resulting in WTW GHG emissions of 10 200 ktonCO$_2$eq. in 2030. Biodiesel is added to the 100 000 less BEV scenario, to reach the same level of WTW GHG emissions. This way the biodiesel share is 44 %.

Differences in fuel volumes and electricity consumption are seen in the table. A positive value represents an additional amount or cost in the electric scenario, whereas a negative value represents an additional amount or cost in the 100 000 less BEV scenario. Electricity, fossil diesel and FAME consumption is higher in the electric scenario and fossil gasoline, ethanol and HVO consumption is higher in the 100 000 less BEV scenario. Unit costs for liquid fuels are derived from Nylund et al. [140], where the costs are based on CIF ARA (Amsterdam/Antwerp/Rotterdam) market prices on 1.2.2017. A 15 % cost premium is considered for HVO compared to FAME, as HVO does not have a market price. FAME is considered to be rapeseed methyl ester (RME). The prices on renewable fuels are on the same level as presented in [141], where options for increased production of renewable fuels in Finland is assessed.

The electricity price is reflecting the average day-ahead Finnish market price on the Nord Pool spot market [142]. Quantifying the additional cost of the 100 000 extra BEVs in the electric scenario, the additional cost of 9846 € per vehicle obtained in the analysis in chapter 2.2 is used. All costs are considered before tax, which gives a more representative view of the actual total costs related to the two scenarios. Finally, a BEV provides emission reductions throughout its whole lifetime, whereas the emission reduction from biofuels are directly and fully obtained in the specific year. Due to this, the additional cost of BEVs is divided with the average age of a vehicle in the Finnish vehicle fleet in 2016, which is 11.9 years. As a result of this calculation, the additional cost of the electric scenario compared to the 100 000 less BEV scenario is 25 456 thousand euro, reflecting an added cost of 255 euro per additional BEV. Changing the lifetime of the BEVs to 8 years, gives an additional cost of 660€ per additional BEV. Similar cost comparisons could be made for several different scenarios, using the quantitative results obtained from the model.

Table 15 Cost comparison based on model results, of the Finnish electric scenario and a modified electric scenario with 100 000 less BEVs in 2030. The modified scenario has a higher share of HVO.

Cost factor	Difference		Unit cost		Cost (€)
Fossil gasoline	-106 107 796	l	0,40	€/l	- 42 443 118
Ethanol	-15 068 775	l	0,59	€/l	- 8 890 577
Electricity	+ 209 167 706	kWh	0,03	€/kWh	+ 6 787 492
Fossil Diesel	+ 106 614 355	l	0,39	€/l	+ 41 579 598
HVO	-60 213 156	l	0,95	€/l	- 57 202 499
FAME	+ 3 492 563	l	0,83	€/l	+ 2 885 161
Additional cost of BEVs	+ 100 000	Nr.	9 846	€/vehicle	+ 82 739 496
BEV lifetime	11,9	years			
				Total	+ 25 455 553
				Per vehicle	+ 255

11 Conclusions

This study provides a comprehensive analysis on powertrain development scenarios for light-duty vehicles, as well as on road transport energy consumption and GHG emissions in Finland, Sweden and Norway. The electric powertrain is examined in detail, due to its high efficiency and large emission reduction potential when clean electricity is used. Barriers to a wide and rapid adoption of electric vehicles are recognized as the high price and low range. The price of a battery electric vehicle is noted to be significantly higher than the price of conventional ICE vehicle, both considering production price and consumer purchase price. Fuels costs are, however, significantly lower for electric vehicles, and expanding the cost analysis to consider total cost of ownership improves the competitiveness of the electric powertrain. A relation is found, that electric vehicles with high mileages are more cost competitive, due to the low cost of fuel. Still, it is noted that customers do not fully acknowledge the cost competitiveness of electric vehicles from a perspective on total cost of ownership, but are more sensitive to the purchase price. Currently, electric vehicles benefit from extensive subsidies in all three countries, which likely has had a large impact on the electric vehicle adoption so far.

Both barriers to electric vehicle adoption, high price and low range, are related to the electric vehicle battery, which suffers from an inferior energy density compared to liquid fuels. However, new battery technologies and improvements, especially in anode and cathode materials, can offer higher energy densities and lower costs. Additional cost savings from larger production volumes can also contribute to a continuation of the trend with falling battery prices. Assessing reported production costs of batteries by market leaders between 2007 and 2014, the annual cost reductions were found to have been around 8 %. Assuming continuing annual cost reductions of 8 %, the production costs could reach levels around 150 €/kWh in 2020 and 100 €/kWh in 2025. Some manufacturers have already announced that they have achieved such productions costs, which highlights the great uncertainty surrounding the production cost of batteries.

A high degree of unpredictability is related to the future of powertrains in the vehicle fleet. In this study, two scenarios were created for the shares of powertrains in new light-duty vehicle sales between 2017 and 2050. Scenarios for HDV and buses from Giacosa [7] were included when assessing the whole vehicle fleet. The electric scenario describes the diffusion of electric vehicles, including PHEV and HEV, with the help of a Bass diffusion methodology, relying on data on historical diffusion [9]. The conservative scenario is a less aggressive continuation of the current trend for powertrain shares in the national vehicle markets. Examining the development of specific CO_2 emissions of light-duty vehicle new registrations in the scenarios, it is evident that electric vehicles are needed to meet the 95 gCO_2/km target for passenger cars set in EC 443/2009 and 147 gCO_2/km target for light commercial vehicles defined in EU 510/2011. Even though these targets are for vehicle manufacturers on EU wide vehicle sales, they can be considered to have an impact on vehicle sales in Finland, Sweden and Norway.

To assess the impact of these development scenarios, a quantitative model was created were results can be obtained regarding GHG emissions, fuel consumption and vehicle fleet in all three countries until 2050. Due to the urgent need of GHG emission reductions, a good understanding of the road transport sector from the perspective of energy demand and GHG emissions is important. The road transport system has a high degree of complexity with many impacting parameters, which is why the model is necessary to get a grasp on the quantities of energy consumption and GHG emissions related to a certain development scenario. Examining the model results, an important insight is the high inertia of the vehicle fleet due to the slow renewal of vehicles. As a result, the impact of efficiency improvement of new vehicles, or vehicles with more efficient powertrains, is very small as it only affects a small part of the vehicle fleet. On the other hand, changes in the amount of biofuels or the total transport need, has a direct impact of energy consumption and GHG emissions, which can be seen in the sensitivity analysis.

The aim of this study was to construct road transport development scenarios and compare the impact of a certain development scenario with national TTW GHG emission reduction targets in Finland, Sweden and Norway. Based on the model results, it is evident that reaching the targets is very challenging in all three countries. It will require large amounts of biofuels and significant improvements in vehicle efficiency. The national emission reduction targets are very ambitious and are not met in the constructed scenarios. In the electric scenario, a physical bioenergy share of liquid and gaseous fuels of 45% in Finland, 67% in Sweden and 51% in Norway would be needed to meet the national reduction targets. The high transport need growth and slow fleet renewal, are recognized as factors working against a fast reduction of emissions in the road transport segment. Due to the high energy density requirement of HDVs, the potential of electrification is limited, which further highlights the importance of biofuels. Striving for significant and fast emission reductions, the introduction of E10 in Sweden and Norway, as well as E20 in all three countries is of great importance.

Finally, both efficiency improvements and biofuels are certainly needed to achieve significant emission reductions. Road transport policies should be designed to promote the development of the most cost-efficient emission abatement option. Achieving large GHG emission reductions in road transport is clearly challenging, and further analysis related to scenario costs should be performed to evaluate the most efficient way of emission reductions. Due to the worldwide immense need of emission reductions, a broader perspective on fuel and energy demand would also be required, to ensure that the most cost-efficient options for GHG emission reductions are used.

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Appendix 1

Table 1 Emission factors and energy factors for energy carriers [11], [17], [118], [143].

Energy carrier components	u WTT [gCO2e/MJ]	g TTW [gCO2e/MJ]	h WTW [gCO2e/MJ]	e_t TTW [MJ/l]	Bio-share
Fossil gasoline	14,2	75,2	89,4	32,2	0 %
Ethanol	26,8	0,0	26,8	21,3	100 %
MTBE	26,8	58,7	85,5	26,1	22 %
ETBE	26,8	47,4	74,2	27,2	37 %
TAME	26,8	61,7	88,5	28,0	18 %
TAEE	26,8	53,4	80,2	29,0	29 %
Biogasoline	26,8	0,0	26,8	32,0	100 %
Synthetic gasoline	26,8	0,0	26,8	32,0	100 %
Future gasoline 1	26,8	0,0	26,8	30,0	100 %
Future gasoline 2	26,8	0,0	26,8	30,0	100 %
Fossil diesel	15,9	74,5	90,4	35,9	0 %
HVO	27,1	0,0	27,1	34,3	100 %
FAME	27,1	0,0	27,1	33,1	100 %
FT-diesel	27,1	0,0	27,1	34,3	100 %
BTL	27,1	0,0	27,1	34,3	100 %
GTL	27,1	0,0	27,1	34,3	100 %
Future diesel 1	27,1	0,0	27,1	34,3	100 %
Future diesel 2	27,1	0,0	27,1	34,3	100 %
ED95	26,2	3,8	29,9	21,8	0 %
CNG - natural gas	8,7	59,4	68,1	36,2	0 %
CNG - biogas	16,8	0,0	16,8	34,9	100 %
LNG - natural gas	21,3	59,4	80,7	-	0 %
LNG - biogas	21,3	0,0	21,3	-	100 %
Fossil hydrogen	104,3	0,0	104,3	-	-
Renewable hydrogen	13,0	0,0	13,0	-	-
Electricity Finland	40,8	0,0	40,8	-	-
Electricity Sweden	3,9	0,0	3,9	-	-
Electricity Norway	0,0	0,0	0,0	-	-
Renewable electricity	0,0	0,0	0,0	-	-

Appendix 2

Table 1 Electric scenario PC vehicle fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 879 949	701 708	844	2 196	245	18 824	426	3 582	1 820	0	2	0	20
2020	1 784 004	747 082	16 739	20 105	299	65 162	503	3 591	2 374	0	2	0	16
2025	1 585 368	669 505	115 237	85 728	341	205 811	540	3 237	2 966	0	2	0	10
2030	1 345 377	510 727	300 967	184 458	285	385 426	427	2 181	3 374	0	2	0	5
2035	1 098 525	351 996	500 805	283 959	173	547 156	248	1 068	3 541	0	1	0	2
2040	852 965	232 618	689 050	369 709	89	669 091	126	526	3 571	0	0	0	1
2045	654 012	153 455	847 282	434 769	46	747 550	65	245	3 576	0	0	0	0
2050	506 146	100 958	976 966	482 416	19	796 954	25	91	3 588	0	0	0	0

Table 2 Electric scenario LCV fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	8 725	293 537	170	0	0	0	0	5	245	0	0	0	11
2020	6 314	303 374	496	102	0	307	0	5	400	0	0	0	12
2025	3 363	305 319	2 700	730	0	2 191	0	4	1 458	0	0	0	11
2030	1 781	297 096	11 301	1 964	0	5 892	0	3	4 382	0	0	0	8
2035	906	278 583	26 605	3 338	0	10 014	0	2	8 049	0	0	0	5
2040	435	257 514	43 901	4 609	0	13 827	0	1	11 676	0	0	0	3
2045	207	239 403	59 840	5 570	0	16 711	0	1	14 631	0	0	0	2
2050	84	227 251	72 038	6 210	0	18 630	0	0	16 650	0	0	0	1

Table 3 Electric scenario HDV fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 315	91 282	1	0	0	3	2	66	81	1	0	0	93
2020	1 034	86 706	11	0	12	3	53	61	100	2	0	0	81
2025	771	81 368	72	0	72	2	281	47	101	34	0	0	61
2030	558	76 807	228	0	225	1	801	33	81	148	0	0	43
2035	349	71 966	445	0	442	1	1 482	21	59	310	0	0	27
2040	191	68 463	681	0	672	0	2 173	12	41	470	0	0	16
2045	97	66 647	910	0	902	0	2 859	5	28	600	0	0	9
2050	40	66 140	1 136	0	1 140	0	3 562	2	20	696	0	0	3

Table 4 Electric scenario Bus fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	16	11 865	13	0	0	0	0	0	40	0	2	0	16
2020	10	12 423	127	0	0	0	17	0	35	0	2	0	15
2025	5	12 635	380	0	0	0	94	0	29	0	2	0	12
2030	2	12 323	836	0	0	0	279	0	37	0	9	0	8
2035	1	11 585	1 317	0	0	0	535	0	44	0	31	0	4
2040	0	10 802	1 710	0	0	0	778	0	43	0	66	0	2
2045	0	10 247	2 005	0	0	0	993	0	32	0	108	0	1
2050	0	9 777	2 232	0	0	0	1 183	0	18	0	146	0	0

Table 5 Conservative scenario PC vehicle fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 879 949	701 708	844	2 196	245	18 824	426	3 582	1 820	0	2	0	20
2020	1 778 340	763 412	6 224	17 665	299	57 589	503	3 591	5 970	0	2	0	16
2025	1 638 352	741 435	52 810	56 936	341	145 847	540	3 237	22 274	0	2	0	10
2030	1 552 518	648 448	141 132	109 927	285	242 974	427	2 181	52 134	0	2	0	5
2035	1 490 530	531 025	228 390	162 104	173	322 980	248	1 068	85 489	0	1	0	2
2040	1 447 007	421 125	304 566	205 699	89	380 617	126	526	116 772	0	0	0	1
2045	1 437 853	329 440	360 227	238 542	46	420 518	65	245	143 027	0	0	0	0
2050	1 448 071	258 235	396 971	263 030	19	452 355	25	91	163 587	0	0	0	0

Table 6 Conservative scenario LCV fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	8 725	293 537	170	0	0	0	0	5	245	0	0	0	11
2020	6 660	303 736	332	0	0	19	0	5	364	0	0	0	12
2025	4 348	308 594	975	0	0	689	0	4	1 424	0	0	0	11
2030	3 345	310 047	1 919	0	0	3 014	0	3	4 356	0	0	0	8
2035	2 916	307 455	2 881	0	0	6 330	0	2	8 037	0	0	0	5
2040	2 718	303 977	3 724	0	0	9 754	0	1	11 677	0	0	0	3
2045	2 659	301 677	4 338	0	0	12 677	0	1	14 633	0	0	0	2
2050	2 659	301 423	4 743	0	0	14 747	0	0	16 645	0	0	0	1

Table 7 Conservative scenario HDV fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 315	91 282	1	0	0	3	2	66	81	1	0	0	93
2020	1 103	86 617	2	0	0	3	25	61	167	2	0	0	81
2025	942	81 194	10	0	0	2	127	47	384	34	0	0	61
2030	780	76 837	40	0	0	1	362	33	688	148	0	0	43
2035	569	72 459	92	0	0	1	667	21	984	310	0	0	27
2040	350	69 513	159	0	0	0	974	12	1 249	470	0	0	16
2045	200	68 311	233	0	0	0	1 254	5	1 474	600	0	0	9
2050	100	68 488	316	0	0	0	1 518	2	1 670	696	0	0	3

Table 8 Conservative scenario Bus fleet in Finland, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	16	11 865	13	0	0	0	0	0	40	0	2	0	16
2020	10	12 477	74	0	0	0	7	0	44	0	2	0	15
2025	5	12 808	199	0	0	0	49	0	83	0	2	0	12
2030	2	12 720	406	0	0	0	164	0	195	0	1	0	8
2035	1	12 240	593	0	0	0	340	0	346	0	1	0	4
2040	0	11 685	730	0	0	0	514	0	484	0	0	0	2
2045	0	11 334	826	0	0	0	661	0	582	0	0	0	1
2050	0	11 066	892	0	0	0	778	0	638	0	0	0	0

Table 9 Electric scenario PC vehicle fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	2 888 035	1 529 782	7 532	16 355	2 477	54 075	1 050	224 808	43 692	0	0	0	46
2020	2 570 511	1 864 006	62 736	96 163	5 781	158 950	3 189	191 186	51 778	0	0	0	35
2025	2 159 264	1 639 583	369 295	332 224	7 571	432 648	6 847	114 595	55 218	0	0	0	22
2030	1 765 255	1 040 644	923 701	651 973	7 167	789 957	9 989	46 443	54 895	0	0	0	12
2035	1 393 787	543 616	1 490 813	937 214	5 563	1 107 693	12 154	18 312	54 424	0	0	0	5
2040	1 064 567	291 399	1 941 258	1 127 972	4 071	1 313 843	13 291	9 204	55 131	0	0	0	3
2045	841 617	184 821	2 249 651	1 229 508	3 077	1 407 495	13 874	3 922	55 735	0	0	0	1
2050	692 564	127 757	2 492 884	1 287 173	2 212	1 438 005	14 362	1 778	56 299	0	0	0	1

Table 10 Electric scenario LCV fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	52 441	471 375	1 552	0	0	56	0	1 700	7 578	0	0	1	9
2020	34 677	543 815	8 300	381	0	811	763	1 361	8 456	0	0	2	7
2025	18 743	580 375	34 958	2 253	0	4 537	4 505	745	6 698	0	31	2	4
2030	9 579	569 294	85 827	6 253	0	12 520	12 506	314	3 884	0	967	1	2
2035	4 440	534 382	145 545	11 565	0	22 699	22 693	144	1 862	0	4 037	1	1
2040	1 939	497 330	197 748	18 336	0	33 120	33 117	83	842	0	9 083	0	0
2045	871	460 320	238 466	26 179	0	43 121	43 120	37	415	0	14 146	0	0
2050	381	424 352	274 067	35 190	0	53 426	53 426	14	206	0	18 042	0	0

Table 11 Electric scenario HDV fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 074	79 434	0	0	0	0	23	0	821	0	0	57	14
2020	770	80 730	18	0	4	0	147	0	805	3	0	45	9
2025	481	85 092	129	0	103	0	826	0	673	98	5	27	5
2030	301	89 133	360	0	413	0	2 274	0	505	412	139	15	3
2035	194	92 719	659	0	927	0	4 075	0	324	804	569	8	1
2040	110	97 001	976	0	1 501	0	5 737	0	193	1 108	1 269	5	1
2045	55	101 834	1 294	0	2 065	0	7 290	0	108	1 126	1 980	3	0
2050	22	107 242	1 627	0	2 639	0	8 847	0	57	791	2 542	1	0

Table 12 Electric scenario Bus fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	36	11 017	38	0	0	0	27	0	2 346	0	0	390	26
2020	41	12 185	397	0	0	0	157	0	1 467	0	0	151	7
2025	23	12 583	1 124	0	0	0	516	0	457	0	1	19	0
2030	6	11 916	2 078	0	0	0	1 040	0	107	0	41	2	0
2035	1	11 105	2 817	0	0	0	1 513	0	32	0	158	0	0
2040	0	10 545	3 334	0	0	0	1 891	0	9	0	332	0	0
2045	0	10 061	3 741	0	0	0	2 245	0	1	0	476	0	0
2050	0	9 617	4 152	0	0	0	2 624	0	0	0	557	0	0

Table 13 Conservative scenario PC vehicle fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	2 888 035	1 529 782	7 532	16 355	2 477	54 075	1 050	224 808	43 692	0	0	0	46
2020	2 579 338	1 852 894	46 748	81 303	5 844	191 259	3 194	190 180	53 085	0	0	0	35
2025	2 352 879	1 724 744	173 733	229 938	7 852	484 502	6 940	113 581	59 385	0	0	0	22
2030	2 241 571	1 306 646	386 152	423 404	7 655	859 854	10 097	45 538	61 586	0	0	0	12
2035	2 076 146	957 539	606 260	642 107	6 213	1 203 493	12 161	17 728	62 656	0	0	0	5
2040	1 880 549	789 536	782 910	824 035	4 873	1 450 276	13 269	8 895	64 207	0	0	0	3
2045	1 702 469	714 724	903 630	960 522	4 036	1 602 073	13 863	3 704	65 171	0	0	0	1
2050	1 560 054	667 125	993 545	1 068 687	3 350	1 709 300	14 362	1 598	65 972	0	0	0	1

Table 14 Conservative scenario LCV fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	52 441	471 375	1 552	0	0	56	0	1 700	7 578	0	0	1	9
2020	35 894	543 251	5 180	0	0	1 126	1 077	1 362	11 047	0	0	5	7
2025	20 662	585 450	16 157	0	0	4 138	4 106	745	19 343	0	0	9	4
2030	10 891	597 932	33 133	0	0	8 559	8 544	314	27 959	0	0	12	2
2035	5 171	600 277	50 359	0	0	12 979	12 973	144	34 678	0	0	13	1
2040	2 247	603 919	63 682	0	0	17 224	17 221	83	38 768	0	0	14	0
2045	1 016	604 608	72 670	0	0	21 265	21 263	37	40 848	0	0	15	0
2050	470	604 786	79 698	0	0	25 514	25 514	14	42 281	0	0	15	0

Table 15 Conservative scenario HDV fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 074	79 434	0	0	0	0	23	0	821	0	0	57	14
2020	832	80 481	0	0	0	0	59	0	1 062	3	0	104	8
2025	577	84 867	12	0	0	0	233	0	1 495	98	0	156	4
2030	383	89 953	46	0	0	0	595	0	1 976	412	0	193	2
2035	265	95 442	104	0	0	0	1 043	0	2 426	804	0	220	1
2040	170	101 937	175	0	0	0	1 471	0	2 855	1 107	0	246	0
2045	109	108 836	256	0	0	0	1 866	0	3 234	1 313	0	270	0
2050	71	115 955	345	0	0	0	2 262	0	3 590	1 461	0	292	0

Table 16 Conservative scenario Bus fleet in Sweden, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	36	11 017	38	0	0	0	27	0	2 346	0	0	390	26
2020	41	12 004	342	0	0	0	140	0	1 715	0	0	151	7
2025	24	12 082	799	0	0	0	428	0	1 347	0	0	19	0
2030	6	11 548	1 235	0	0	0	861	0	1 487	0	0	2	0
2035	1	11 267	1 474	0	0	0	1 267	0	1 561	0	0	0	0
2040	0	11 281	1 626	0	0	0	1 556	0	1 599	0	0	0	0
2045	0	11 354	1 750	0	0	0	1 733	0	1 648	0	0	0	0
2050	0	11 459	1 881	0	0	0	1 887	0	1 692	0	0	0	0

Table 17 Electric scenario PC vehicle fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 198 158	1 254 476	97 359	30 488	2 310	55 609	735	0	116	0	116	0	16
2020	970 619	1 318 781	209 932	129 084	6 566	153 782	841	0	564	0	199	0	10
2025	867 018	1 175 698	376 760	291 076	9 627	325 026	988	0	1 462	0	243	0	5
2030	890 514	864 263	550 644	494 138	12 459	508 988	925	0	2 322	0	287	0	2
2035	961 222	576 956	684 354	681 863	10 717	654 605	738	0	2 967	0	219	0	1
2040	1 066 112	368 155	792 112	825 435	6 352	747 902	676	0	3 252	0	120	0	0
2045	1 167 166	230 805	885 933	943 515	3 901	796 768	656	0	3 352	0	78	0	0
2050	1 253 361	147 607	969 079	1 046 886	2 054	820 889	638	0	3 426	0	36	0	0

Table 18 Electric scenario LCV fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	31 766	460 640	2 566	55	2	0	0	0	394	0	0	0	3
2020	17 397	496 922	8 668	43	2	557	557	0	1 138	0	0	0	2
2025	8 265	511 961	27 199	25	1	3 446	3 446	0	3 424	0	0	0	1
2030	3 746	503 718	55 939	11	1	9 666	9 666	0	7 010	0	0	0	0
2035	1 431	486 043	84 575	5	0	17 369	17 369	0	10 596	0	0	0	0
2040	555	470 039	106 316	3	0	24 139	24 139	0	13 261	0	0	0	0
2045	236	458 217	121 520	1	0	29 550	29 550	0	14 891	0	0	0	0
2050	94	450 020	133 386	0	0	34 159	34 159	0	15 871	0	0	0	0

Table 19 Electric scenario HDV fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	2 675	67 296	2	0	0	0	0	0	253	0	0	0	70
2020	1 215	64 204	3	0	0	0	40	0	635	2	0	0	43
2025	502	64 327	27	0	0	0	321	0	1 119	85	0	0	21
2030	219	66 728	78	0	0	0	986	0	1 474	345	0	0	9
2035	95	70 104	136	0	0	0	1 741	0	1 754	640	0	0	4
2040	35	74 525	188	0	0	0	2 326	0	1 994	856	0	0	2
2045	13	80 415	244	0	0	0	2 802	0	2 233	1 028	0	0	1
2050	5	87 190	307	0	0	0	3 240	0	2 473	1 181	0	0	0

Table 20 Electric scenario Bus fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	309	15 272	10	0	0	0	0	0	733	0	5	0	1
2020	146	14 556	7	0	0	0	1	0	641	0	3	0	1
2025	60	14 053	42	0	0	0	69	0	564	0	0	0	0
2030	25	13 357	144	0	0	0	307	0	648	0	0	0	0
2035	10	12 929	275	0	0	0	711	0	736	0	0	0	0
2040	4	12 638	381	0	0	0	1 095	0	799	0	0	0	0
2045	1	12 567	453	0	0	0	1 347	0	842	0	0	0	0
2050	1	12 569	523	0	0	0	1 523	0	874	0	0	0	0

Table 21 Conservative scenario PC vehicle fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	1 198 158	1 254 476	97 359	30 488	2 310	55 609	735	0	116	0	116	0	16
2020	970 619	1 318 781	209 932	129 084	6 566	153 782	841	0	564	0	199	0	10
2025	867 018	1 175 698	376 760	291 076	9 627	325 026	988	0	1 462	0	243	0	5
2030	890 514	864 263	550 644	494 138	12 459	508 988	925	0	2 322	0	287	0	2
2035	961 222	576 956	684 354	681 863	10 717	654 605	738	0	2 967	0	219	0	1
2040	1 066 112	368 155	792 112	825 435	6 352	747 902	676	0	3 252	0	120	0	0
2045	1 167 166	230 805	885 933	943 515	3 901	796 768	656	0	3 352	0	78	0	0
2050	1 253 361	147 607	969 079	1 046 886	2 054	820 889	638	0	3 426	0	36	0	0

Table 22 Conservative scenario LCV fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	31 766	460 640	2 566	55	2	0	0	0	394	0	0	0	3
2020	17 397	496 922	8 668	43	2	557	557	0	1 138	0	0	0	2
2025	8 265	511 961	27 199	25	1	3 446	3 446	0	3 424	0	0	0	1
2030	3 746	503 718	55 939	11	1	9 666	9 666	0	7 010	0	0	0	0
2035	1 431	486 043	84 575	5	0	17 369	17 369	0	10 596	0	0	0	0
2040	555	470 039	106 316	3	0	24 139	24 139	0	13 261	0	0	0	0
2045	236	458 217	121 520	1	0	29 550	29 550	0	14 891	0	0	0	0
2050	94	450 020	133 386	0	0	34 159	34 159	0	15 871	0	0	0	0

Table 23 Conservative scenario HDV fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	2 675	67 296	2	0	0	0	0	0	253	0	0	0	70
2020	1 215	64 204	3	0	0	0	40	0	635	2	0	0	43
2025	502	64 327	27	0	0	0	321	0	1 119	85	0	0	21
2030	219	66 728	78	0	0	0	986	0	1 474	345	0	0	9
2035	95	70 104	136	0	0	0	1 741	0	1 754	640	0	0	4
2040	35	74 525	188	0	0	0	2 326	0	1 994	856	0	0	2
2045	13	80 415	244	0	0	0	2 802	0	2 233	1 028	0	0	1
2050	5	87 190	307	0	0	0	3 240	0	2 473	1 181	0	0	0

Table 24 Conservative scenario Bus fleet in Norway, by powertrain and year

	Gasoline	Diesel	BEV	Gasoline PHEV	Diesel PHEV	Gasoline HEV	Diesel HEV	FFV	CNG	LNG	FCV	ED95	Other
2016	309	15 272	10	0	0	0	0	0	733	0	5	0	1
2020	146	14 556	7	0	0	0	1	0	641	0	3	0	1
2025	60	14 053	42	0	0	0	69	0	564	0	0	0	0
2030	25	13 357	144	0	0	0	307	0	648	0	0	0	0
2035	10	12 929	275	0	0	0	711	0	736	0	0	0	0
2040	4	12 638	381	0	0	0	1 095	0	799	0	0	0	0
2045	1	12 567	453	0	0	0	1 347	0	842	0	0	0	0
2050	1	12 569	523	0	0	0	1 523	0	874	0	0	0	0

Appendix 3

Table 1 Base fuel scenario in the Finnish model

	2016	2020	2025	2030	2035	2040	2045	2050
Vol% of gasoline grades								
95 E10	65 %	85 %	90 %	69 %	53 %	41 %	31 %	24 %
95 E20	0 %	0 %	5 %	26 %	43 %	56 %	66 %	74 %
98 octane	35 %	15 %	5 %	4 %	4 %	3 %	3 %	2 %
Vol% of diesel components								
Fossil	95 %	78 %	75 %	56 %	59 %	59 %	59 %	59 %
HVO	5 %	18 %	19 %	34 %	34 %	34 %	34 %	34 %
FAME	0 %	4 %	6 %	7 %	7 %	7 %	7 %	7 %
CNG biogas share of energy	54 %	54 %	54 %	54 %	54 %	54 %	54 %	54 %
LNG biogas share of energy	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
Electricity (gCO2eq./MJ)	40,4	38,8	36,7	34,7	32,7	30,6	28,6	26,5

Table 2 Base fuel scenario in the Swedish model

	2016	2020	2025	2030	2035	2040	2045	2050
Vol% of gasoline grades								
95 E10	96 %	97 %	92 %	71 %	54 %	42 %	32 %	25 %
95 E20	0 %	0 %	5 %	26 %	43 %	56 %	66 %	74 %
98 octane	4 %	3 %	3 %	3 %	2 %	2 %	2 %	2 %
Vol% of diesel components								
Fossil	68 %	61 %	40 %	20 %	16 %	13 %	13 %	13 %
HVO	25 %	32 %	53 %	73 %	77 %	80 %	80 %	80 %
FAME	7 %	7 %	7 %	7 %	7 %	7 %	7 %	7 %
CNG biogas share of energy	72 %	75 %	78 %	82 %	87 %	91 %	95 %	95 %
LNG biogas share of energy	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
Electricity (gCO2eq./MJ)	3,9	3,7	3,5	3,3	3,1	2,9	2,7	2,5

Table 3 Base fuel scenario in the Norwegian model

	2016	2020	2025	2030	2035	2040	2045	2050
Vol% of gasoline grades								
95 E10	98 %	98 %	93 %	72 %	56 %	43 %	33 %	26 %
95 E20	0 %	0 %	5 %	26 %	43 %	56 %	66 %	74 %
98 octane	2 %	2 %	2 %	1 %	1 %	1 %	1 %	1 %
Vol% of diesel components								
Fossil	88 %	78 %	65 %	60 %	57 %	56 %	56 %	56 %
HVO	7 %	15 %	28 %	33 %	36 %	37 %	37 %	37 %
FAME	5 %	7 %	7 %	7 %	7 %	7 %	7 %	7 %
CNG biogas share of energy	50 %	54 %	59 %	65 %	72 %	80 %	88 %	97 %
LNG biogas share of energy	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
Electricity (gCO2eq./MJ)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Appendix 4

Table 1 Energy consumption (PJ) by energy carrier in Finnish electric scenario

	2016	2020	2025	2030	2040	2050
Fossil gasoline	53,14	50,06	46,83	43,19	35,23	28,64
Ethanol	3,30	3,51	3,65	4,12	4,26	3,95
Fossil diesel	102,63	84,78	75,47	52,17	39,61	34,71
HVO	4,82	18,83	18,51	28,99	22,01	19,29
FAME	0,00	3,49	5,58	5,73	4,35	3,81
CNG - natural gas	0,08	0,09	0,13	0,23	0,43	0,51
CNG - biogas	0,09	0,10	0,15	0,27	0,49	0,59
Electricity	0,04	0,42	2,18	5,14	10,25	13,20
Rest	0,00	0,01	0,06	0,24	0,65	0,82

Table 2 Energy consumption (PJ) by energy carrier in Finnish conservative scenario

	2016	2020	2025	2030	2040	2050
Fossil gasoline	53,14	50,13	47,69	46,60	45,85	46,43
Ethanol	3,30	3,52	3,72	4,44	5,55	6,40
Fossil diesel	102,63	85,47	78,40	56,90	47,04	41,95
HVO	4,82	18,98	19,23	31,62	26,14	23,31
FAME	0,00	3,52	5,80	6,25	5,16	4,60
CNG - natural gas	0,08	0,18	0,60	1,38	2,80	3,59
CNG - biogas	0,09	0,21	0,70	1,59	3,25	4,16
Electricity	0,04	0,17	0,96	2,14	3,84	4,49
Rest	0,00	0,01	0,06	0,24	0,60	0,72

Table 3 Energy consumption (PJ) by energy carrier in Swedish electric scenario

	2016	2020	2025	2030	2040	2050
Fossil gasoline	99,11	80,04	69,35	64,30	56,42	48,84
Ethanol	4,62	6,56	6,66	7,04	6,94	6,77
Fossil diesel	122,78	121,29	76,72	33,64	16,92	16,38
HVO	43,50	59,44	96,31	114,13	99,46	96,33
FAME	11,13	12,73	12,32	10,62	8,40	8,13
CNG - natural gas	1,62	1,23	0,75	0,49	0,21	0,12
CNG - biogas	4,09	3,60	2,71	2,29	2,17	2,20
Electricity	0,24	1,50	6,47	13,99	24,92	29,75
Rest	0,00	0,01	0,19	0,87	2,84	2,98

Table 4 Energy consumption (PJ) by energy carrier in Swedish conservative scenario

	2016	2020	2025	2030	2040	2050
Fossil gasoline	99,11	84,34	83,35	89,96	96,15	93,91
Ethanol	4,62	6,82	7,77	9,52	11,83	13,07
Fossil diesel	122,78	120,83	78,14	36,34	20,61	20,68
HVO	43,50	59,22	98,08	123,30	121,16	121,61
FAME	11,13	12,69	12,55	11,48	10,23	10,27
CNG - natural gas	1,62	1,36	1,16	1,03	0,57	0,33
CNG - biogas	4,09	3,99	4,21	4,83	5,73	6,21
Electricity	0,16	0,86	2,67	5,26	9,18	10,89
Rest	0,00	0,01	0,18	0,70	1,53	1,76

Table 5 Energy consumption (PJ) by energy carrier in Norwegian electric scenario

	2016	2020	2025	2030	2040	2050
Fossil gasoline	32,20	26,35	24,03	23,47	21,05	17,54
Ethanol	1,12	1,70	1,85	2,23	2,56	2,43
Fossil diesel	98,91	86,43	64,37	49,02	35,94	35,18
HVO	7,19	15,36	25,91	26,25	22,87	22,40
FAME	5,46	7,11	6,35	5,31	4,16	4,07
CNG - natural gas	0,44	0,32	0,19	0,14	0,02	0,00
CNG - biogas	0,44	0,37	0,27	0,27	0,09	0,08
Electricity	1,43	3,89	7,86	12,05	18,28	22,38
Rest	0,29	0,02	0,17	0,72	2,01	2,62

Table 6 Energy consumption (PJ) by energy carrier in Norwegian conservative scenario

	2016	2020	2025	2030	2040	2050
Fossil gasoline	32,20	30,52	34,33	41,24	53,32	59,17
Ethanol	1,12	1,97	2,64	3,92	6,49	8,20
Fossil diesel	98,91	87,95	67,93	54,33	42,33	41,98
HVO	7,19	15,63	27,34	29,09	26,95	26,73
FAME	5,46	7,24	6,70	5,88	4,89	4,85
CNG - natural gas	0,44	0,42	0,44	0,47	0,34	0,05
CNG - biogas	0,44	0,48	0,63	0,88	1,34	1,77
Electricity	1,31	2,64	4,43	6,17	8,37	9,67
Rest	0,29	0,01	0,10	0,38	0,78	0,95

Appendix 5

Table 1 TTW GHG emissions (ktonCO$_2$eq.) by vehicle segment in the Finnish electric scenario

	2016	2020	2030	2040	2050
PC	6 971	6 315	4 695	3 576	2 906
LCV	1 341	1 123	797	669	589
HDV	2 874	2 312	1 726	1 720	1 730
Bus	467	381	258	221	201

Table 2 TTW GHG emissions (ktonCO$_2$eq.) by vehicle segment in the Finnish electric scenario

	2016	2020	2030	2040	2050
PC	6 971	6 329	5 005	4 390	4 130
LCV	1 341	1 124	825	776	748
HDV	2 874	2 312	1 733	1 735	1 752
Bus	467	384	275	253	243

Table 3 TTW GHG emissions (ktonCO$_2$eq.) by vehicle segment in the Swedish electric scenario

	2016	2020	2030	2040	2050
PC	10 916	10 001	6 660	5 951	5 354
LCV	1 633	1 499	498	331	349
HDV	3 256	3 144	1 227	895	914
Bus	487	468	150	87	82

Table 4 TTW GHG emissions (ktonCO$_2$eq.) by vehicle segment in the Swedish conservative scenario

	2016	2020	2030	2040	2050
PC	10 916	10 077	7 664	7 541	7 298
LCV	1 633	1 503	517	332	335
HDV	3 256	3 143	1 237	917	998
Bus	487	464	158	99	96

Table 5 TTW GHG emissions (ktonCO$_2$eq.) by vehicle segment in the Norwegian electric scenario

	2016	2020	2030	2040	2050
PC	5 719	4 914	3 450	2 912	2 610
LCV	1 807	1 626	1 015	732	600
HDV	1 920	1 830	1 585	1 605	1 818
Bus	381	341	224	181	166

Table 6 TTW GHG emissions (ktonCO$_2$eq.) by vehicle segment in the Norwegian conservative scenario

	2016	2020	2030	2040	2050
PC	5 719	5 053	4 192	4 333	4 532
LCV	1 807	1 648	1 150	979	930
HDV	1 920	1 830	1 606	1 693	1 957
Bus	381	342	251	225	217